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Editor: G. V. JACKS, M.A.

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THE GILGAIED AND BAD-STRUCTURED SOILS OF CENTRAL IRAQ

S. A. HARRIS

(*Land Use Division, Hunting Technical Services Ltd., England*)

Summary

The variable soils of the recent alluvium of parts of Iraq contain horizons falling into two groups, viz. bad-structured horizons which are hard and dense with marked vertical cracking, and well-structured horizons characterized by a friable consistency and higher porosity. Gilgai occurs as the extreme bad-structured phase. The only constant difference in laboratory data between these groups is the low laboratory permeability in the bad-structured horizons. These features cannot be explained using the causes so far put forward for gilgaied soils in Australia, but they suggest an explanation of the process of formation of bad structure (in the agricultural sense) in terms of compaction by weathering agents. It is suggested as being a process which is habitually taking part in the development of solonetz soils, since the latter always seem to be characterized by this bad structure.

Introduction

In this paper it is intended to give a general description of the gilgaied and bad-structured soils of Central Iraq and to note the way in which they differ from the associated normal soils. Details of their pedology will be found elsewhere (Binnie *et al.*, 1956), the classifications being summarized by Smith (1957) and Smith and Robertson (1956).

It is a particularly interesting area since the soils are in the process of being formed on extremely recent calcareous alluvium, and no differentiation into A, B, and C horizons has yet occurred. There is considerable

Fig. 1. An idealized cross-section of a gilgai to show the names given to the different parts.

stratification, while numerous small shallow inland drainage basins occur on the wide areas of otherwise almost flat surfaces. Textures are characterized by an extremely high silt content. Both normal and bad-structured soils may or may not be saline, and sometimes contain appreciable exchangeable sodium. The gilgai appear to be the extreme phase of development of bad structure in these soils.

The term 'gilgai' comes from Australia where it was applied, among others, by Prescott (1931, p. 15) to the 'characteristic alternations of depressions and rises in heavy soils' induced by 'the alternations of wet seasons and floodings on the one hand and of droughts on the other'. The names given to the parts of a gilgai are summarized diagrammatically in Fig. 1. A considerable amount of scattered morphological information is to be found in succeeding C.S.I.R.O. Bulletins, but the main

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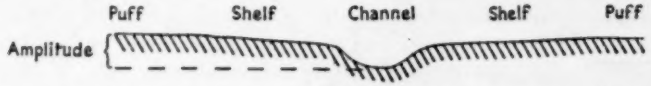

FIG. 1. An idealized cross-section of a gilgai to show the names given to the different parts.

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discussion of the subject was by Hallsworth *et al.* (1955). There seems to be a certain amount of doubt as regards the mechanism of gilgai formation, but little attempt has been made to elucidate the ultimate cause. Gilgais are normally regarded as solonetzic soils. The association

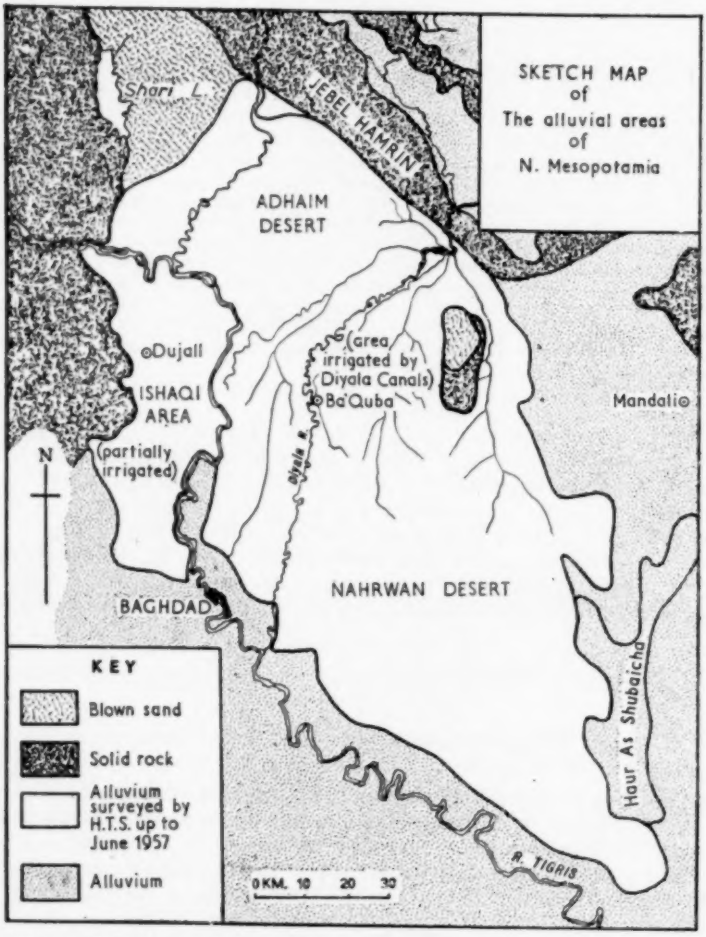


FIG. 2. Sketch map of the alluvial areas of Central Iraq discussed in this paper.

and relation of other bad-structured soils to areas of gilgai are rarely mentioned. Since Australia is an example of an old land surface with mature soils, there is comparatively limited variety of soil profiles and the absence of inland depressions limits the scope of the inquiry there.

Alluvial Soils of Iraq

For two years the writer was engaged on soil survey and land classification for irrigation purposes in Central Iraq. The area covered lies between the beginning of the foothills and Baghdad (Fig. 2) and consists mainly of recent alluvium brought down by the River Tigris and its tributaries. Very locally, soils derived from hill-wash from local solid rock outcrops and from blown sand occur.

The soils show negligible profile development, the active soil processes being salinization and the formation of bad structure over wide areas.

The catena found in the area is shown in a somewhat idealized diagrammatic form in Fig. 3. Various parts or the whole of this catena may sometimes be saline. The underlying coarse material varies in position regardless of the surface soils. Locally the gilgai or the coarse-textured members may be absent, but this structural relationship for the fine-textured soils persists over the whole area of alluvium. The moderately poorly structured soils always occur predominantly around gilgai and marsh areas, although some are associated with conditions of minor leaching of saline tracts.

Analysing the classification of Australian gilgai adopted by Hallsworth *et al.* (1955), the normal, mushroom, lattice, and wavy gilgai form a series of classes related solely to topography. This grouping would therefore seem the most convenient system of classification. The melon-hole and stony gilgai may occur in any of these classes (e.g. McGarity, 1953), and would therefore seem best regarded as varieties.

In Iraq, gilgai fall into three groups:

1. Normal gilgai, sometimes found in large flat areas south-east of Baghdad. Its surface is marked by circular patches of *Aeluropus* sp. on the puff and by circular sink-holes in place of the channels in the other gilgai.
2. Lattice (type-A) gilgai, found mainly on the cultivated land immediately north of Baghdad.
3. A new type, the *depression gilgai*, forming the bulk of the kinds found.

The depression gilgai are complex forms found in the bottom of the numerous shallow, isolated, inland drainage basins. On the outside where the slope is greatest, many gilgai are found which grade inwards via lattice gilgai to an area of normal gilgai. These occur in two main forms:

(*a*) *Type A*, found where the depression is fairly deep. It consists of a thin margin of wavy gilgai surrounding a large area of lattice (type-A) gilgai, e.g. Plate I (*a*). Often in an oval or circular depression; a central channel runs the length of the long axis, though only a short central channel may occur.

(*b*) *Type B*, found in the desert areas south of Baghdad where flatter floored depressions may be found. It consists of an outer margin of wavy gilgai passing into a flat area with normal gilgai, sometimes with lattice (type-A) gilgai occurring in between.

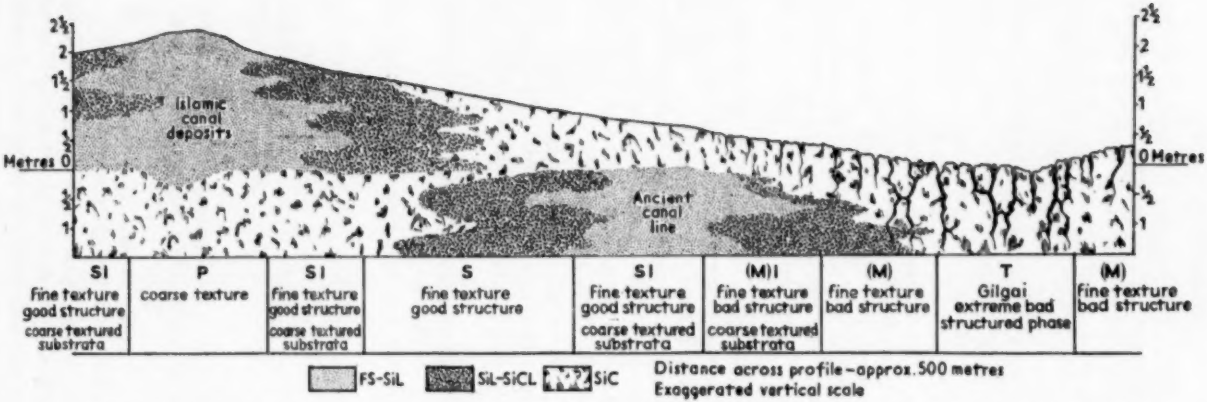

Islamic canal deposits
Ancient canal line
Metres 0
0 Metres
SI fine texture good structure coarse textured substrata
P coarse texture
SI fine texture good structure coarse textured substrata
S fine texture good structure
SI Fine texture good structure coarse textured substrata
(M)I fine texture bad structure coarse textured substrata
(M) fine texture bad structure
T Gilgai extreme bad structured phase
(M) fine texture bad structure
FS-SiL
SiL-SiCL
SiC
Distance across profile–approx. 500 metres
Exaggerated vertical scale

FIG. 3. Diagrammatic cross-section from canal ridge to depression to show the characteristic soil association found on the alluvial soils.

Plate II (*b*) shows an annotated composite example of these two kinds of depression gilgai.

In Iraq there may well be an evolutionary cycle of type-A depression gilgai, passing through type-B depression gilgai to normal gilgai. Type-A depression gilgai only occur in the present and recently irrigated areas where there is considerable relief. During irrigation much sand and silt is deposited along the beds of the irrigation ditches and canals. Every year this is dug out and piled along the bank. When the bank becomes too high, a new canal is dug alongside the old one, and the process is recommenced. As the water is released on to the field during flood irrigation, the bulk of the loss in water velocity and deposition of sediments occurs near the irrigation ditch. Consequently there is a continual process of building up the relief during the existing irrigation. Vegetation cover reduces erosion to a minimum.

In desert areas, no processes occur which tend to increase relief, and sheet wash is at a maximum. The rainfall is infrequent, but very heavy, and ideal for sheet erosion. Under this process, the topography becomes reduced and the depressions gradually filled in. It is in these areas that both normal and type-B depression gilgai are found. Thus there may well be an evolutionary cycle of type-A depression gilgai (Pl. I (*a*)) as the usual form found in areas of moderate relief, passing through type-B depression gilgai to the normal gilgai as soon as this relief becomes destroyed by erosion. This would explain the absence of depression gilgai in Australian examples which are developed in mature soils on an old land surface.

Occasionally, the pattern of puff and shelf may follow the pre-existing topographic pattern, where this has not yet been obscured by surface wash, e.g. the area north-west of Baghdad where the canals cut by the Abbasid caliphs had dissected the surface drainage pattern, producing numerous small depressions (see Pl. II and Binnie *et al.*, 1956, vol. ii, p. 178). Plate III is an aerial photograph of part of a very large depression known as the Haur As Shubaicha, which is flooded almost every winter. The old canal or drainage channel pattern shows up quite clearly since it has largely controlled the form of the gilgai channels. Mapping the gilgai was greatly facilitated by the use of aerial photographs, due to the marked pattern formed by the microrelief.

The gilgais in depressions receiving a large runoff or much irrigation water were mainly of the melon-hole variety, i.e. both puff and shelf were hard and sink-holes often occurred. Only a few of the saline gilgais proved to have a soft surface in spite of the high lime content. In areas receiving a moderate amount of runoff, the gilgais were usually intermediate in form. There appeared to be only a slight differentiation into puff and shelf. The amplitude rarely exceeded 60 cm. and generally averaged 22–28 cm. The wavelength varied considerably.

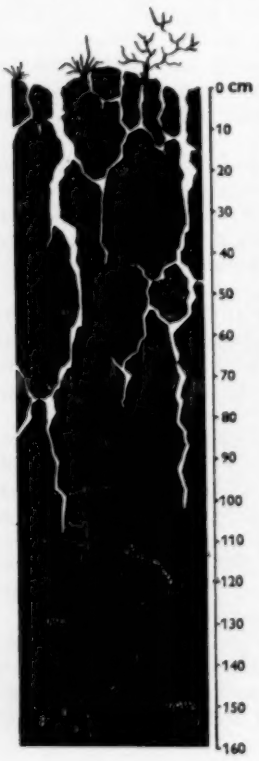
All the bad-structured soils show marked coarse polygonal cracking and usually have a hard surface. Unlike the Australian examples, there is considerable variation in the profiles corresponding to the original stratification of the alluvium. All the alluvial soils may contain both good- and bad-structured horizons.

The bad-structured horizons are characterized by hard or firm consistency when dry or moist, lack of visible pore spaces (except in the surface layer) and high density. They do not absorb water readily. The strong vertical cracks may extend to 150 cm. in extreme cases (see Pl. IV). The good-structured horizons are those which are characterized by a friable, floury, or mellow consistency (dry or moist). They usually contain a moderate amount of visible pores, are of lower density, and absorb water readily.

In gilgai profiles a bad-structured horizon is invariably present, but although most profiles consist entirely of bad-structured horizons, considerable variation may be found, corresponding to original stratification in the alluvium. Gilgai may be found where only 50 cm. of bad-structured silty clay loam overlies friable sand. No shear planes have been seen. There is no evidence for movement of the clay fraction within the profile. The following actual description shows what may be regarded as a typical gilgai profile for most of the cases studied (Pit 1014).

Pit 1014

Gilgai, near a saline ancient-village mound. Shelf has some dead grass and live *Prosopis farcta*, particularly near the puff which has a thicker cover. The puff has marked coarse surface cracking, but not as well developed as on the shelf. Individual cracks may be 4 cm. wide. The amplitude is 30 cm.



0–150 cm. max. 10 YR. Grey-brown silt clay loam. Dry and hard to 50 cm.; over moist and hard; well-developed medium, fine and coarse vertical cracking; the coarse cracking persists to 100 cm., otherwise structureless; very hard consistency throughout, becoming even harder below 100 cm.; moderately porous but dense to 50 cm.; over dense, massive and non-porous; a few roots to depth; gypsum present as microcrystalline veins and aggregates from 70 cm., but never very common.

The moderately bad-structured soils usually found in similar environments with the gilgai are characterized by a bad-structured layer in the top 100 cm. The vertical cracking usually varies from 40 to 90 cm. in depth. As with gilgai, considerable variation in profile is found, ranging from a simple profile similar to Pit 1014 to highly stratified profiles, e.g.:

Pit 1011

One hundred yards from old irrigation canals to the west. Fallow field with *Centaurea* sp., *Prosopis farcta*, and *Aeluropus* sp. Moderate fine and coarse surface cracking.

0–30 cm.	7·5 YR 4/4 loam. Fairly soft and dry; moderately well-developed vertical cracking throughout, with medium angular blocky structure to 5 cm.; hard, brittle consistency; roots present; no visible salts; *Helicella leucosticta* fragments.
30–32 cm.	2·5 Y 4/4 olive-brown fine sand. A free running sand; no visible salts.
32–48 cm.	10 YR 5/3 silt clay loam. Fairly hard and dry; strongly laminated with weak angular blocky structure; hard consistency; no visible salts.
48–50 cm.	2·5 Y 4/4 olive-brown fine sand; as 30–32 cm.
50–160 cm. max.	7·5 YR 5/4 to 58 cm.; over 10 YR 5/2 to 90 cm.; over 7·5 YR 5/4. Silty clay. Moist and hard; strong vertical cracking from 58 to 130 cm.; otherwise structureless; hard consistence throughout; gypsum present from 58 cm.; a few 'shok' roots.

The surface horizons of all soils are almost invariably characterized by an extreme development of large pores (sometimes called 'aero-structure' in the field), except in the extreme solonchak soils which generally have a well-developed crumb structure. These large pores are also found in moderately poorly structured soils and appear to be intermediate between the mellow, well-structured horizons and the dense, badly structured layers.

Some of the non-saline soils are so recent as to have had little time to gain or lose salt. It would therefore seem that loss of structure by leaching a saline soil (Quirk and Schofield, 1955) cannot always have contributed to the formation of the bad structure.

Detailed examination of the bad-structured soils suggests that the mechanism of gilgai formation operating in Iraq may be similar to that described for the Australian examples of melon-hole gilgai on chernozem soils (McGarity, 1953). The cracks are commonly found to be partly or wholly filled with surface material by the end of the dry summer. No evidence of mixing of the upper and lower horizons on the puff has been found so far. Carbonate concretions have not been found on the surface of the puff, although they are often present in the profile.

Evidence was found that the surface structure of a bad-structured, fine-textured profile may be restored by allowing a good thick turf cover to grow over the land for about three years. In another soil pit in this area, the roots of the grass appear to break up the top 40 cm., producing good structure once again. On the former site of the Haur Damal, near Kut, good-structured soils may be found. At the end of the First World War the area was flooded by break-throughs of the banks of the Tigris (Harris and Adams, 1958). Subsequently, the banks have been strengthened and the Haur has dried up. Now a dense *Salsola* scrub occupies much of the area. Remains of sink-holes and coarse polygonal surface cracking are common, but the soils have reverted to moderately bad-structured and good-structured soils. The unusual characteristic of the structure of these soils is that they appear hard and dense, but have numerous tiny pore spaces (presumably caused by roots) and absorb water readily.

Chemical and Physical Data

All the soils contain between 20 and 35 per cent. calcium carbonate, yet both melon-hole and normal gilgais occur. Gypsum was consistently low, being less than 1 per cent. in almost all the alluvial soils. The gypseous soils in the Ishaqi Project area contained up to 60 per cent. gypsum, but rarely developed gilgai, and then only in marginal areas where the gypsum content was less than 3 per cent. in any horizon. Salinity varied from non-saline to saline, the highest electrical conductivity recorded being 105 mmhos/cm. The salt has probably accumulated due to irrigation without a drainage system (Russel, 1956; Smith, 1957). Carbonate scarcely moves, except under conditions of extreme irrigation and water-logging. Gypsum is very soluble in the local saline irrigation waters (Smith, 1957) and moves fairly freely in the profile.

The values of pH were remarkably constant (at 7·2–8·4) throughout the area, regardless of soil type.

Fig. 4 shows the mechanical composition of the horizons found in all the gilgai soils fully analysed during the course of work in Central Iraq. The material occurring as coarse-textured substrata in gilgais is not included. The field of unstable soils found in all profiles fully sampled is also indicated, as are the limits of 30 per cent. clay (finer than 0·002 mm.)

and 50 per cent. International sand (coarser than 0·02 mm.). The total field is the same as for the finer soils of all kinds found in the same areas.

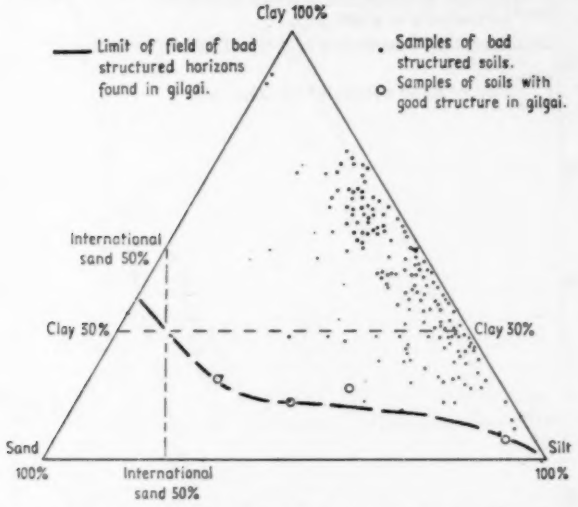


FIG. 4. Triangular diagram of the textures of gilgai horizons encountered on the soil surveys in Central Iraq. The approximate position of the 50% 'International' sand line has been added, using the correction suggested by Marshall, 1947.

TABLE I

Clay Mineral Composition for Selected Samples from Central Iraq

Pit	*NN 481*			*NA 8523*			*I/P 789*	*I/P 369*
Texture				SiCl	SiCL	SiCL	SiL	SiC
Depth (cm.)	0–30	50	140	0–20	50–100	100–50	40–50	440–50
Kaolin	3	3	2	3	3	3	3	3
Mica	4	4	3	4	4	4	4	4
Montmorillonite	3	4	3	3	4	5	4	4
Chlorite	2	2	5	3	2	2	3	3
Quartz	1	1	2	1	1	1	1	1
Calcite	1	1	1	1	1	1	2	2
Palygorskite	1	1	1	1	1	1	2	2
α-Crystobalite	..	..	..	1	..	..	..	..
Goethite	..	..	..	..	..	1	..	..
Felspar	..	..	..	..	..	..	1	2

0–5%, 1; 6–10%, 2; 11–25%, 3; 26–50%, 4; > 50%, 5.

Sand content never exceeds 60 per cent. in horizons in the main part of a gilgai. This suggests that the proportion of sand, silt, and clay may be more important in gilgai formation than the percentage of any one constituent. It is also worth noting that the gilgai-free sandy soils of the area (aeolian deposits) are characterized by over 85 per cent. U.S.D.A. sand (coarser than 0·05 mm.).

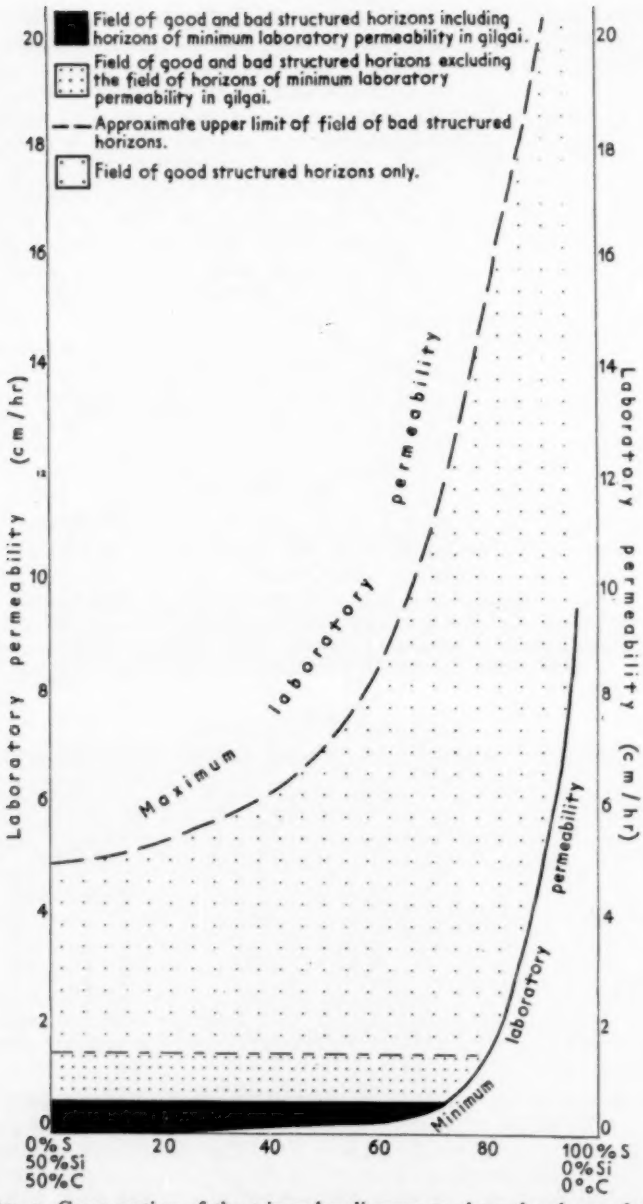


FIG. 5. Cross-section of the triangular diagram to show the shape of the field of laboratory permeabilities of the alluvial soils of Central Iraq.

Table 1 shows the results for clay mineral composition, determined at Rothamsted Experimental Station, of several samples of different textures. No one clay mineral is dominant, mica and montmorillonite

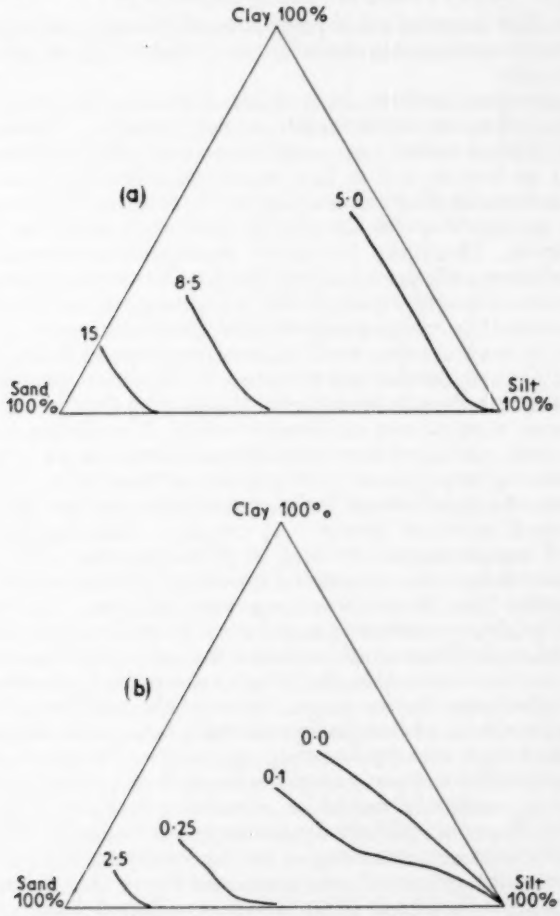


FIG. 6. Maximum (*a*) and minimum (*b*) laboratory-permeability contours for all the horizons fully analysed (based on 8,000 samples).

being present in equal proportions. The minerals are remarkably constant in spite of coming from widely separated localities. Some regular interstratification of montmorillonite and chlorite layers was found.

Results of soluble cation and anion determinations on 1:1 water extracts of bad-structured soils follow the same pattern as those of well-structured soils. Sodium and chloride ions are usually dominant

(Smith, 1957). Sodium chloride is the dominant salt in the saline soils, but a more even distribution of the chlorides and sulphates of calcium, magnesium, and sodium occurs in the other soil types, no one salt being dominant.

Sodium clays occur in a fair proportion of the soils but appear to be equally distributed between the saline well-structured and saline badly-structured soils.

Laboratory permeabilities have shown a much closer relationship to soil structure than any other factors (as was found by Tisdall, 1953, in Australia). This is rather surprising, since these physical tests are often reputed to be inexact and to lack reproducibility. Fig. 5 is a section across the triangular diagram showing the relationship of sand content to laboratory permeability for the alluvial soils of Central Iraq, based on 8,000 samples. Maximum laboratory permeabilities showed a fairly close correlation with sand content ranging from over 15 cm./hr. for 80 per cent. sand to under 5 cm./hr. for less than 5 per cent. sand (Fig. 6). The minimum laboratory permeabilities show extremely low values, falling below 0·25 cm./hr. over most of the texture triangle, and to 0·0 cm./hr. for one-third of the triangle. A definite dependence on the quantity of finer materials available for clogging up the through passages in the coarser material can be demonstrated. The difference between maximum and minimum laboratory permeabilities is far greater than could reasonably be explained by laboratory and field errors. Also shown in Fig. 5 are the approximate limits of laboratory permeabilities of the bad-structured horizons (about 1·45 cm./hr.), and the field for the horizons of minimum permeability in gilgai (less than 0·60 cm./hr.). These appear to be independent of the mechanical composition. Saline gilgais usually have lower laboratory permeabilities than non-saline gilgais, while gilgai-marsh soils may have somewhat higher values than in the other forms. The normal and saline well-structured soils often have laboratory permeabilities exceeding these values, although some exceedingly low values may also be found. Most of the horizons encountered in all the soils contained less than 50 per cent. sand, while the laboratory permeabilities were usually less than 2·5 cm./hr. Since other factors, notably topography and surface drainage, are also involved, not all soils having low permeabilities would be expected to have bad structure.

The limited number of field densities appeared superficially to show a similar relationship to structure as the laboratory permeability. Thus the samples of the gilgai soil were extremely dense, the highest density recorded being 1·89 g./c.c. More data are required before the exact relationship can be determined.

Field permeabilities on the earlier desert surveys proved unreliable owing to the difficulty of avoiding high values due to penetration of water down cracks. Further discussion of the results will be found in Smith (1957) and the appropriate reports. A revised method has been used in the surveys of the irrigated areas, but this gives a value for a given depth below the water table. It cannot be used on any given horizon and usually gives an average result for several layers. The general conclusion is that field permeabilities decrease with depth in these soils—the reverse

of what would be expected from mere compaction by the weight of the horizons above.

Formation of Bad Structure

So far, two main mechanisms of gilgai formation have been suggested, both incorporating the earlier ideas, and based on the two cases found in Australia:

1. Where there is definite mixing of the material in the puff (Hallsworth *et al.*, 1955). These profiles exhibit shear planes. All the stony variety of gilgai are of this type. Aitchison (1953) gave the theoretical side of this process.
2. Where there appears to be no mixing of the material in the puff (McGarity, 1953). Shear planes were not described from the profile.

The examples from Iraq clearly fall in the second group.

Australia has a comparatively old land surface. Its soils have had plenty of time to become adjusted to the weathering agents at present prevailing, i.e. they are mature soils. Thus most of the soils show well-developed A, B, and C horizons, in contrast to the young alluvial soils of Central Iraq which have mainly been deposited in the last few millennia (see Harris and Adams, 1958).

As regards causes, the external causes operating in Australia also apply in Iraq, although the effect of the 5½-in. average yearly rainfall of the Baghdad area is considerably modified locally by the flooding of the isolated depressions.

Suggested internal causes for the Australian examples are (1) high clay content, increasing with depth; (2) increasing exchangeable sodium with depth; (3) increasing exchange capacity with depth; (4) ability to transmit a thrust; (5) high volume expansion increasing markedly with depth.

Apart from item 4, these causes certainly do not apply in all the Iraqi examples, but a physical cause would seem likely.

Since we are dealing with very young, rather unconsolidated materials, the fundamental cause of gilgai formation in Iraq could be compaction under the action of weathering agents. Only this hypothesis appears satisfactorily to explain the extremely large range of laboratory permeabilities for any given mechanical composition. The pattern of low surface field permeabilities increasing with depth, low laboratory permeabilities and high field densities suggests downpacking of the surface layers accompanied by the blocking of the through passages between the larger grains (i.e. the effective porosity) by the finer material. It would also explain the extremely low values of minimum laboratory permeability, although even lower results are theoretically possible.

A sand consisting of spherical grains in the tightest possible packing (rhombohedral) has an effective porosity of only 9·30 per cent. (Graton and Fraser, 1935). Thus, in theory, only 10 per cent. clay by volume (or else 15 per cent. by weight of clay of density 1·5 g./c.c.) would be required completely to block up the through passages in a sand consisting of spherical grains. The sand grains found in nature are never completely spherical, and the more angular the grains the smaller the

effective porosity under the closest possible packing. Initial packing in freshly deposited materials is much poorer than can be attained artificially in the laboratory. Thus, freshly deposited clays may have an initial porosity of 85 per cent. (Pettijohn, 1957, p. 86). Subsequent compaction has been noted as being affected by depth below the surface, texture, and incidence of deformation. Compaction is usually regarded as not affecting sands much, but becoming increasingly important with increase in clay content. The possibility of compaction under normal weathering if a given deposit does not become buried has not been considered, as far as the writer is aware.

A Possible Origin of Bad-structured Soils

The alternate moist and dry conditions might cause a downpacking of the soils, possibly helped or caused by dispersion of the clay minerals. Normal hydration of the clay may cause swelling and hydration of the flakes, accompanied by a tendency to re-orientation in the direction of least resistance. On drying out, the clay minerals shrink and the other grains would then pack in more closely round them. At a particular stage in downpacking, the effective pores are closed, whereas the bulk of the trapped air tends to migrate into large closed pores as bubbles when the deposit is wetted. After these are expelled, the downpacking can proceed farther only slowly. Not surprisingly, the maximum degree of downpacking theoretically possible is never actually achieved.

If this interpretation of the data is correct, a given soil would appear to become gradually compacted under the influence of alternate wetting and drying under suitable external conditions. From the time of initial deposition, a given surface deposit will be liable to this process until such time as it either ceases to compact any farther or else is either eroded away or buried sufficiently deeply to be out of the influence of weathering agents. In the latter case, the superincumbent load would tend to continue the process.

This surface compaction may or may not continue until the effective porosity is nil, depending on the intensity of the external factors (e.g. incidence of flooding), the mineralogical and mechanical composition, and the chemical stability of the material causing the increased density. Thus removal of a soluble salt, e.g. gypsum, by surface water will cause voids (see, for example, Herroro, 1957). As the density increases, so the ability of the material to transmit a thrust will increase. In extreme cases, compaction will continue until the trapped air has been almost completely expelled from the soil, as in most gilgaied soils.

The mechanism suggested by Hallsworth *et al.* (1955) would appear to be an extreme example of thrusting movements caused by much higher volume expansion at depth. Where volume expansion either does not vary, or varies only irregularly in the profile, e.g. Iraq, the result described by McGarity (1953) will be found.

Initially the expansion and contraction of the clay minerals with alternate hydration and desiccation will cause only minor cracking. The lack of ability of loose material to transmit pressure without deformation will permit the take-up in the surrounding material of any swelling due

to fragments which have fallen down cracks in dry weather. This will add to the speed of compaction. Gradually the soil will become sufficiently dense to transmit internal pressures bodily through it. This phase will also be characterized by marked surface cracking which, in turn, will increase the liability to material falling in during dry weather. It is under these conditions that the gilgai-forming mechanism of Hallsworth *et al.* (1955) will become operative.

Once the degree of compaction necessary for gilgai formation has been achieved, mere levelling of the surface will be quite insufficient to prevent the reappearance of gilgai. Once the disturbed surface layer has lost its major voids, the soil will recommence gilgai formation.

The process may not be irreversible in nature. There should be an equilibrium set up between those factors tending to cause compaction, e.g. alternate wetting and drying, high temperature, incidence of flooding, high montmorillonite content, and presence of exchangeable sodium, and those tending to cause voids in the soil. The presence of the leaching or movement of salts and the effect of burrowing animals and roots will tend to break up or produce spaces within the soil. Ploughing helps the break-up of the surface layers. Thus, according to this hypothesis, the soil structure should reflect the state of this equilibrium at any one time and place.

Relation to Theories of Solonetz Formation

There does not appear to be any single accepted definition of a solonetzic soil which covers all variations which have from time to time been described under this heading. One common factor, however, which seems to appear in all soils described as solonetz is the presence of a poorly structured horizon (in the agricultural sense). On this basis, the bad-structured soils of Central Iraq could be regarded as solonetzic soils. Gilgai soils, generally accepted elsewhere as being solonetzic, occur in Iraq as the extreme phase of development of bad structure.

In the examples studied in Iraq, the chemical definition of a solonetz does not usually apply, and considerable variation of profile occurs. The hypothesis put forward in this paper lays emphasis on the process of formation of bad structure, which, it is suggested, is likely to be of general occurrence in the formation of solonetz soils. The key factor in this process appears to be the balance between factors tending to compact the soil and those causing voids. The fundamental environmental conditions, allowing wetting and drying of the soil, which affect this balance include climate, drainage, and topography. Considerable depths of soil material with a high clay content, or the presence of sodium clays, will naturally tend to favour the trend towards compaction and solonetz formation, but are not in themselves the ultimate cause. In contrast, in the case of solonchak soils, the balance is weighted in favour of good structure, usually because the fundamental conditions are unfavourable. These soils are usually found on slightly higher land where rain water runs off the surface into the depressions. As a result, favourable conditions for compaction only occur in the flooded areas, while the initial porous nature of the higher land remains unimpaired.

Intermediate stages have also been reported, such as the 'takyr' surface on a solonchak (Joffe, 1949, p. 544), but the hypothesis here discussed allows for such cases. The 'takyr' surface occurs in slight hollows in the surface of a solonchak. The latter is usually on a slight ridge allowing better drainage, but the slight undulations provide miniature inland drainage basins which hold just enough water to give adequate wetting and drying to allow for compaction and the formation of bad structure in the top 10 cm.

Conclusions

None of the causes so far put forward for Australian examples fully explains the gilgai soils of Iraq, although the mechanism of formation may be the same as that described by McGarity (1953). The evidence from physical tests, notably laboratory and field permeability, suggested that in Central Iraq the cause might be compaction of the surface layers. A given horizon appeared to be liable, under suitable external conditions, to become badly structured as soon as the laboratory permeability fell below 1·45 cm./hr. Gilgais could be formed by a fairly thin horizon within the top 100 cm., where the laboratory permeability was less than 0·60 cm./hr.

The whole process is suggested to be demonstrating compaction caused by weathering agents. An equilibrium is suggested to occur between the factors tending to produce compaction and those tending to create voids in a given surface deposit. Thus, in Iraq, the compaction would be attributed to the very favourable mechanical composition of most of the sediments and the environment in which external causes were extremely suitable for gilgai formation. No outside influence, e.g. a thick grass cover, or chemical solution makes the deposit noticeably more porous. The relation of this process in these bad-structured and gilgaied soils to the process of formation of the solonetzic soils in general is discussed.

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The author is indebted to the Development Board, Ministry of Development, Government of Iraq, for their permission to publish the original data included in this paper. Thanks are also due to Messrs. Binnie, Deacon, and Gourley, Sir Murdoch MacDonald and Partners, and Messrs. Hunting Technical Services of London, in the service of whom the work was carried out. Gratitude must also be expressed to Drs. T. N. Jewitt, J. F. Kirkaldy, and R. Smith, and Messrs. V. C. Robertson and C. Thomas for reading through the manuscript, and to the members of Hunting Technical Services soil survey field teams for their discussions in the field. Grateful acknowledgement is also due to the Pedology Department of Rothamsted Experimental Station for the clay-mineral determinations.

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Hunting Aerosurveys Ltd.

(*a*) Vertical aerial photograph of an area of type-A depression gilgai, 55 kilometres north-east of Baghdad

(*b*) Annotated vertical aerial photograph of an area of type-B depression gilgai from the Nahrwan Desert. An outer zone of wavy gilgai (1) grades inwards via a zone of type-A lattice gilgai (2) into an area of normal-type gilgai (3)

S. A. HARRIS—PLATE I

Hunting Aerosurveys Ltd.

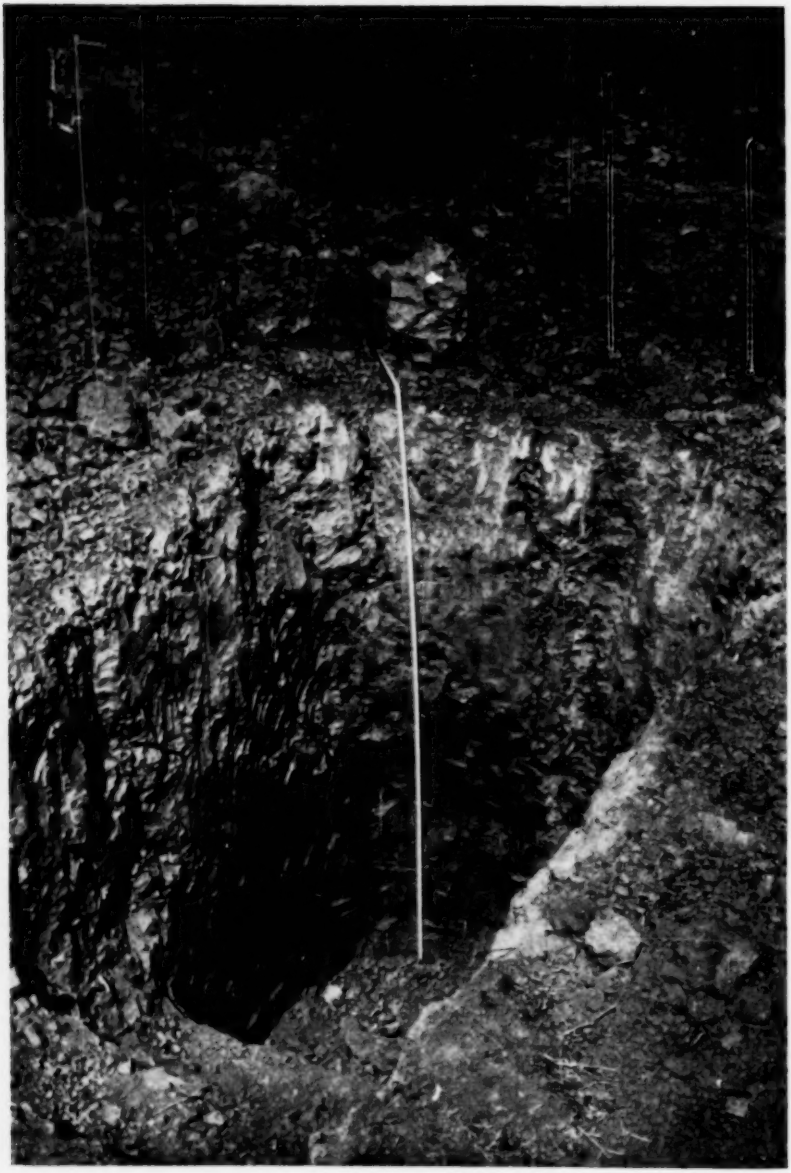
Vertical aerial photograph of part of the Ishaqi area, north-west of Baghdad. Note the way the surface is dissected into small depressions by the remains of the Abbasid irrigation system. In the bottom of each of these inland drainage basins a small gilgai has formed

S. A. HARRIS—PLATE II

Hunting Aerosurveys Ltd.

Vertical aerial photograph of part of the Haur As Shubaicha in the east of the Nahrwan Desert. Note the way the old canal or drainage channel pattern shows through the gilgai channels in the centre of the photograph

S. A. HARRIS—PLATE III



A typical gilgai profile, Pit L/D 209. Note the marked vertical cracking and prismatic structure in this dense soil

S. A. HARRIS—PLATE IV

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PROBLEMS OF SOIL HISTORY. PODZOL DEVELOPMENT AT GOODLAND AND TORR TOWNLANDS, CO. ANTRIM, NORTHERN IRELAND

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Summary

The formation of podzols with well-marked iron pans on boulder clay soils overlying chalk is described. A sub-peat soil at Goodland is to be regarded as a fossil soil with two podzol profiles superimposed. The upper podzol formed in a relatively short time prior to the growth of the overlying blanket bog following tillage which helped to accelerate the rate at which podzolization occurred. A well-marked iron pan in a podzol at Torr has developed during the past hundred years. The formation of an impermeable humus layer within the top few inches of such soils leads to waterlogged conditions suitable for the development of blanket bog over them. This humus layer effectively seals the underlying podzol from waterlogged or gleying conditions.

Accepting the hypothesis that the podzol at Goodland is a fossil soil, a chronology for soil development is proposed using archaeological material as dating evidence.

THE study of the rate at which soil processes take place has always been difficult, for there are few intrinsic soil properties the analysis of which will yield such data (cf. Jenny, 1941, chap. 3). In recent years attention has been given to the results of soil development over long periods of time, with regard to changes in mineral composition (e.g. Dahl, 1954) and in profile development (e.g. Carter, 1956; Carter and Sokoloff, 1954; Flint, 1949; Horberg, 1956; Richmond, 1955). For soil changes within much shorter periods, Dimbleby (1957) has provided valuable evidence based on changes in amounts of soil pollen, and Zeuner (1951, 1955) and Cornwall (1953) have related different phases in soil developments to archaeological material. The recognition of fossil and relict soils by Kubiena, Zeuner, and others (see Osmond, 1956, 1957) has been of outstanding importance in the solution of some problems of soil history. In Ireland a number of 'buried' soils have been described by O'Kelly (1951), but alteration subsequent to their burial has rendered it impossible to obtain a satisfactory chronology for soil development in these cases.

In this paper an attempt is made to correlate various soil and archaeological features and to establish a chronology for the soil processes which have been operative during the post-glacial period in a limited area of north Antrim.

In the townlands of Goodland and Torr to the east of Ballycastle (Fig. 1), at a height of about 700 ft. above sea-level, there are extensive areas of chalk covered with a varying depth of drift. This drift is normally a medium loam derived from a wide variety of rocks, and now largely decalcified. However, it must originally have contained a considerable amount of chalk if the numerous flints remaining in it are an accurate guide. This undulating country is covered in part by heavily grazed

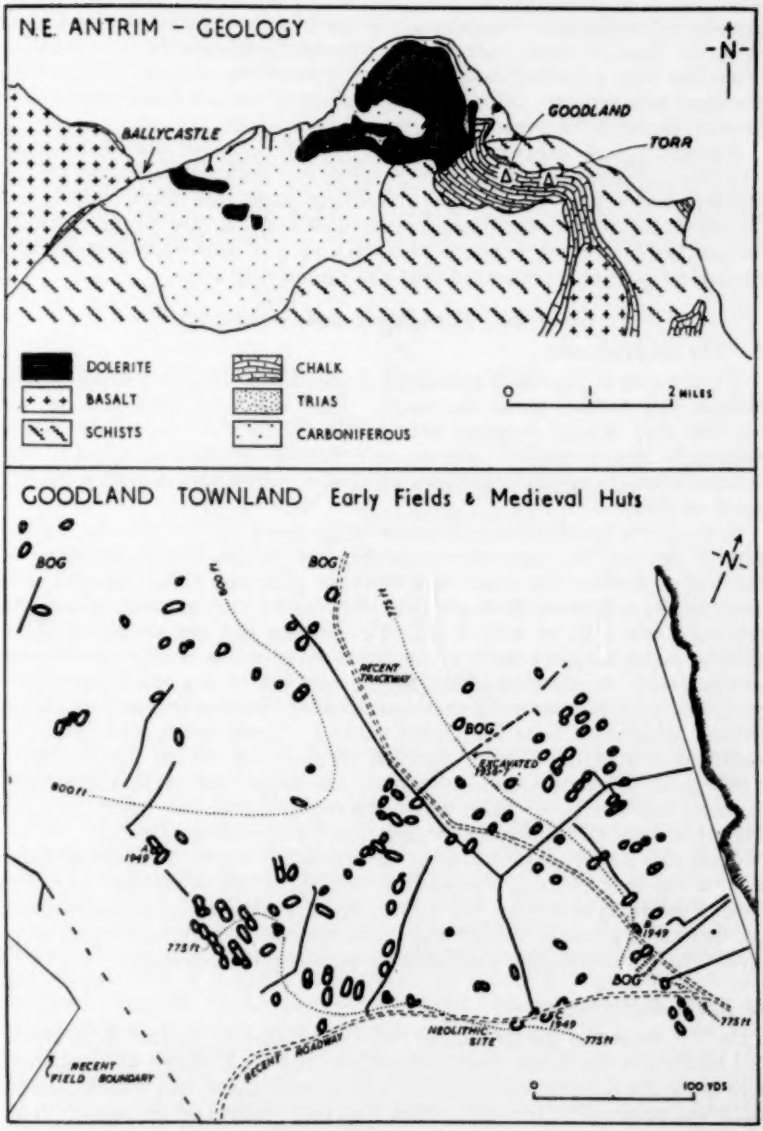
N.E. ANTRIM - GEOLOGY
N
BALLYCASTLE
GOODLAND
TORR
DOLERITE
BASALT
SCHISTS
CHALK
TRIAS
CARBONIFEROUS
0 1 2 MILES
GOODLAND TOWNLAND Early Fields & Medieval Huts
N
BOG
BOG
BOG
BOG
BOG
RECENT TRACKWAY
EXCAVATED 1954
800 ft
775 ft
1949
NEOLITHIC SITE
RECENT ROADWAY
RECENT FIELD BOUNDARY
0 100 YDS

FIG. 1

grassland, the pastures containing considerable amounts of *Festuca* sp., and in part by blanket-peat bog, the fringes of the bogland often being marked by vigorous colonies of rushes (*Juncus effusus/conglomeratus*) (Fig. 1). Rush-infested pastures are common although the solid chalk is often less than a foot below the surface. Most of the area has been neither enclosed nor recently tilled although traces of earlier field systems can be seen beyond the present margins of cultivation.

Archaeological excavations by Mr. H. J. Case of the Ashmolean Museum, Oxford, provided the impetus for work on problems of soil history in this area (Case, 1953). During these and other excavations (Sidebotham, 1950) it was possible to study a large number of soil sections, including many lying beneath peat. An area of some 1,000 sq. ft. was cleared of peat and excavated into the underlying soil.

Goodland: Topography and Archaeology

A. *The neolithic site*

To the east of the chalk grassland at Goodland there is a small area of blanket bog several acres in extent. This bog has developed on the boulder clay which deepens here as the surface of the chalk slopes eastwards into a shallow depression. Smaller patches of blanket bog occur elsewhere on the grassland, generally in those areas with a thicker cover of drift.

A neolithic ritual site was discovered beneath the peat at the feather edge of the boulder clay where this thins out against the eastern slope of the chalk. Excavation revealed a series of pits dug within an oval area bounded by a shallow ditch cut into the boulder clay or chalk to a depth varying from 1 ft. to 2 ft. 6 in. All the pits and the enclosing ditch yielded archaeological finds of neolithic type, while similar finds were also scattered at random in the top few inches of the soil beneath the peat. Several pits as well as the enclosing ditch contained boulders around which artefacts had been packed. Fairly numerous boulders occurred at a higher level in the soil than that at which the pits were recognized, some bearing a relation to the holes beneath them, but the majority not doing so. The pits were recognizable only after the iron pan which was present over the area had been broken through.

After the peat had grown over the neolithic site to a depth of some 6 in. a number of large stones had been piled on what was then the ground surface, and near the stones some potsherds of indeterminate age were also placed. Within the lower foot of the peat also there were several layers containing considerable amounts of charcoal.

B. *Early field system*

On the slopes of the grassland there are traces of ancient field banks and ditches of uncertain date (Proudfoot, 1957). Beneath an excavated field bank the old ground surface could be recognized and the associated ditch was seen to cut through a thin iron pan which had developed in an area where the boulder clay covering the chalk was only 14–15 in. deep. Some of these field boundaries have been partly covered by small areas of blanket bog.

C. *Medieval huts*

After the abandonment of these fields for tillage, and subsequent degrading of the banks and filling of the ditches, a large number of huts were built in late medieval times.

Goodland: Pedology

A. *The neolithic site*

The soil associated with the neolithic site beneath the blanket bog was a well-developed podzol. Immediately beneath the peat was a layer of dark greasy humus, quite distinct in many sections from the overlying peat. It was blacker in colour and more compact than the peat, and

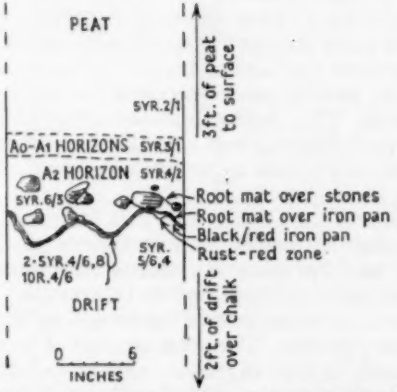

FIG. 2. Sub-Peat profile, Goodland, County Antrim. (Munsell colour of air-dry samples.)

1–2 in. thick. Beneath this was a greyish horizon never less than 4 in. deep and almost stoneless at the top. There were slight signs of humus staining in this horizon but no signs of gleying, and the only structures visible were fine root channels. At the base of this horizon was a zone containing many small stones of flint, schist, basalt, and other igneous rocks. Beneath this but sometimes incorporating the stones with it was a hard compact iron pan, less than $\frac{1}{4}$ in. thick. The upper surface of the pan was black with a very thin layer of humus over it, consisting partly of amorphous humus and partly of roots which had penetrated as far as this, then formed a slight mat over the top of the pan, and finally decayed. Samples of the grey soil above the iron pan were taken at 1-in. intervals from a section where the pan was less than 6 in. below the base of the peat. Considerable difficulty was experienced in removing the organic matter from the soil and the pre-treatment losses were very high, as Table 1 shows. The coarser fractions were determined by sieving, the finer by the hydrometer method.

The percentage of clay in sample 4, taken from the stony layer round which the iron pan has formed, is higher than in the upper samples of

TABLE 1

Fraction	*Samples at 1-in. intervals below peat.*			
	1	*2*	*3*	*4*
	%	%	%	%
Coarse sand, > 0·2 mm.	11·1	19·5	10·5	37·8
Fine sand, 0·2–0·22 mm.	39·4	46·8	60·6	31·6
Silt, 0·02–0·002 mm.	7·0	7·3	9·4	8·3
Clay, < 0·002 mm.	4·5	4·4	3·5	6·3
Pre-treatment loss	38	22	16	16

the profile, a feature which has been noted in other podzol profiles (Robinson, 1949, p. 86). This feature need not be due to pedogenesis, as Evans and Dahl (1955) have noted that forest clearance and tillage seem to leave soils more susceptible to the removal of finer materials.

Immediately beneath the hard red crust of the pan was a thin band of rust-red soil, which, like the pan, contrasted markedly in colour with the brown drift beneath. This drift was almost completely decalcified, but possessed, particularly near the top, a weakly developed crumb structure which was probably a physical aggregation rather than a true biological crumb structure.

Where its depth over the underlying chalk increased, further horizons could be clearly seen. A redder, stonier layer with incipient iron pan developed round and between the stones was noted about halfway between the upper pan just described and the chalk.

A complete series of samples was taken at less than 2-in. intervals throughout this long profile. The total amount of iron was determined colorimetrically using an acid-digestion method and an adaptation of the thioglycollic method in use at the London University Institute of Archaeology's Environmental Laboratory (Cornwall, 1958). Figures refer to total analyses as it was not possible to isolate the clay fraction satisfactorily. This method also has the advantage of including the iron in the pan formed round small stones which it would be impossible to separate for inclusion with clay-fraction analyses.

The concentration of iron in the upper pan and the leached nature of the upper grey layer are clear. No less clear is the high amount of iron in the lower stony layer as compared with layers above and below it. It seems reasonable to suggest that in the section there are two superimposed profiles and the drawing has been labelled accordingly. If the amount of iron concentrated in the upper pan, in the rust-red zone immediately below this and in the next 2 in. of soil (B_1-B_2) is scaled out through the first foot of the whole profile it is found that there is sufficient iron present to give a value throughout this upper part of the profile similar to that recorded from A_2.

The following sequence of events based on the evidence of the whole profile could then be suggested.

1. A period of moderate leaching of the soil with gradual accumulation of iron in a relatively broad zone at a depth of some 15–18 in. Gradual decalcification of the upper part of the soil.

2. A period of more intense leaching with accumulation of iron in a narrow zone and the formation of a definite iron pan at a depth of some 6–8 in. Complete decalcification of that part of the profile above the iron pan.

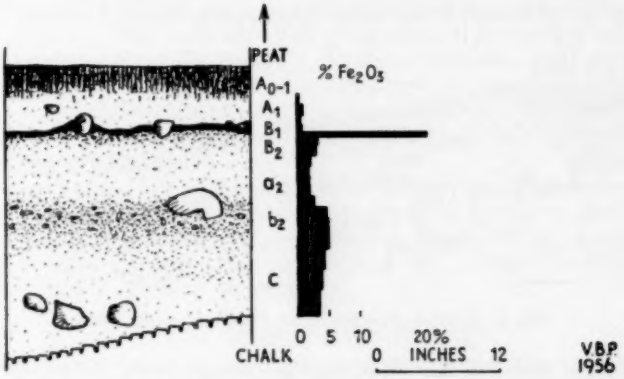

FIG. 3. Goodland Townland, County Antrim, Sub-Peat soil.

To elucidate this sequence and suggest a chronology for it the soil profile has to be considered in relation to the neolithic site and the overlying peat. Before this can be done, however, it is necessary to consider the soil profiles on the grassland (B) and at Torr.

B. *Early field system*

On the slopes of the grassland where a clearly defined field bank and ditch were partly overlain by a small area of incipient blanket bog with vigorous growth of *Juncus* several sections were cut, the most important being shown in Fig. 4. The field bank lies to the right of the ditch and is not shown on the section. Below the top few inches of soil and humus there is an intensely black humus layer which thins out over the ditch. Two iron pans are visible in the section, a thinly developed one at a depth of 6 in. and a very well marked one at about 12 in. The lower pan which is very similar to that described from the neolithic site was cut through when the field ditch was dug. The upper pan occurs at the interface between an upper looser loam and a lower more compact one. Associated with it is a layer of small stones, partly incorporated with the pan, that seems to be the nucleus around which the pan has formed. Above the upper pan the soil is slightly greyer than it is below, but the whole profile above the lower pan has been leached and is much paler in colour than the reddish-brown soil at the base of the profile above the chalk. Neither of these pans seems to have been formed by the lateral movement of iron down slope. Sections cut through the field bank where it has been covered by the incipient blanket bog reveal similar profiles in which the intense black humus layer below the top few inches of soil can still be recognized. This layer seems to be quite impermeable

and to be causing the waterlogged or damp conditions in which the *Juncus* is flourishing. If these conditions were being caused by the iron pan and not by the humus layer there should be some evidence of gleying above the pan, but no such evidence has been noted. The humus layer can, perhaps, be most accurately described as an A_H horizon (Kubiena, 1953, p. 22) although it has to be remembered that the narrow horizon

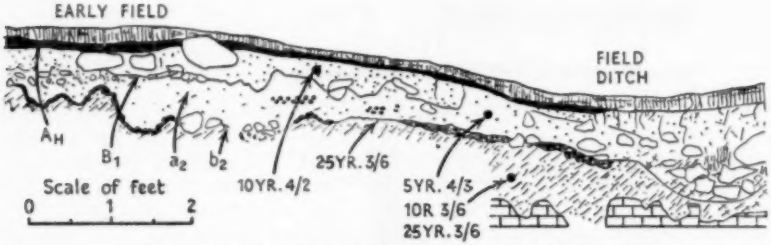

FIG. 4. Section through Early Field and Field Ditch.

immediately above it has more mineral matter in it. The edge of the *Juncus* area is quite irregular, and there is no doubt that *Juncus* is expanding outwards onto the surrounding grassland wherever this development of the sub-surface humus layer inhibits drainage.

The importance of these sections for the present argument is that they clearly indicate podzol formation preceding the development of blanket bog. The podzol beneath the bog is sealed from the waterlogged conditions of the developing bog by the impermeable humus layer below the surface. As the peat develops this layer tends to merge with the peat humus. However, on occasions it can still be recognized as it was in the profile of the neolithic site, where a black compact humus (A_0–A_1 horizons of Fig. 3) could be distinguished from the overlying peat. This sub-peat podzol is thus to be regarded in its main characteristics as a fossil soil (Kubiena, 1953, p. 295) remaining largely unaffected by the overlying blanket bog and present vegetation.

It must be stressed at this point that the recognition of the sub-peat podzol at Goodland as a fossil soil does not necessarily mean that all sub-peat podzols are fossil soils. Many of them probably are, but there is considerable variation in the types of soils found beneath the blanket bogs which cover many gently sloping hillsides in Northern Ireland at a height of 600–800 ft. above sea-level. In general the sub-peat soils have been leached and iron pan has formed in some areas, while the original humus-rich layer near the old ground surface can often be recognized. If these soils were the result of continuous pedogenesis during the period of bog formation the sub-peat soils should be relatively uniform, and should show considerable signs of gleying such as Muir (1934) has described from Scotland, where soils with peaty surface layers or soils beneath considerable depths of peat commonly exhibit gleyed characteristics. Few of the Northern Irish soils that have been examined by the writer beneath blanket bog exhibit any features which

would indicate that gleying has taken place at any stage in their history, and the 'water system' of the peat seems to be unrelated to the soils beneath. A tentative proposal that two water systems are involved might be made here: an upper system associated with the surface vegetation and the peat, and a distinct lower system associated with the sub-peat mineral soil. During excavations at Goodland it was found that the sub-peat soil was quite dry even when water was running out of the peat down the walls of the cuttings. In these Northern Irish fossil soils there is no visible indication, and at Goodland no analytical indication, of the upward movement of minerals through the sub-peat soils, nor of the presence of iron compounds in the overlying peat, such as Salmi (1955) has noted in Finland.

If the sub-peat podzol at Goodland is, as we have suggested, a fossil podzol, we have also to account for the duplication of iron pans in the soil of the neolithic site (A) and, incidentally, for the similar condition in the soil of the early fields on the downland (B). The profile from Torr suggests reasons for this.

Torr: Topography and Pedology

Commercial excavation of a narrow trench across the townlands of East and West Torr provided an opportunity to examine soil profiles over a considerable area. The profile described (Fig. 5) was taken in an abandoned field on a small level shoulder from which the ground sloped fairly steeply upwards. The site is topographically similar to the neolithic site at Goodland (A), and the underlying chalk is likewise covered by boulder clay. Clear traces of spade-cultivated rigs (Evans, 1945, pp. 90–93) are visible in the field which has a cover of poor grasses and is surrounded on its lower sides by rush-fringed blanket bog. Topography and vegetation suggest that this is not an area of cut-over bog, and it seems reasonably certain that the area in which the field is situated has never been covered by peat.

Two zones of iron accumulation are noticeable in the profile; a broad zone some 12–14 in. below the surface and a thin but distinct iron pan at a depth of 6 in., as shown in Fig. 5 and Table 2.

The amounts of iron extracted by Tamm's acid-oxalate method are high in the top few inches of the profile and are consistently higher than the amounts extracted by the acid-digestion method in the upper part of the profile as a whole. The lower zone of iron accumulation, visible in the field and indicated by the acid-digestion method, is not apparent in the acid-oxalate extracts.

A few inches below the surface there is a black humus-rich layer which could not be isolated from the soil above when sampling the profile. The figures for alkali-soluble humus determined colorimetrically (Cornwall, 1958) thus fail to distinguish this layer, but they bring out the large percentage of humus present throughout the profile and the increase in humus in the lower zone of iron accumulation. It can be clearly seen in the sections exposed that the upper iron pan has formed at the base of cultivation, marked not only by the development of the pan itself but also by a change from a looser topsoil to a more compact

soil below, and by a layer of small stones. The lower zone of iron accumulation represents the effects of leaching prior to the cultivation of the ground in spade ridges.

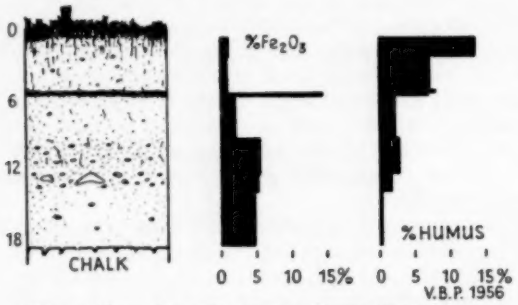

FIG. 5. Torr, County Antrim. Formerly Cultivated Soil. (Fe_2O_3 percentages by Acid Digestion method.)

TABLE 2

Samples depth from surface	% Fe_2O_3	
	Acid-digestion method	*Tamm's acid-oxalate*
1–2½ in. . . .	1·1	7·5
2½–5½ in. . . .	1·0	1·9
5½ in. above pan . .	1·0	2·9
5½ in. pan . . .	14·5	38·0
5½–9½ in. . . .	2·0	10·0
9½–12½ in. . . .	5·5	5·0
12½–14 in. . . .	5·3	3·5
14–18 in. . . .	4·6	4·3

McConaghy has drawn the writer's attention to profiles described by him near Ballygawley (McConaghy, 1957) in which the lower iron pan is thought to be more recent than the upper. The evidence at Torr that the upper iron pan has formed at the base of cultivation and the indications that the pan is still forming exclude a similar interpretation for this section. There seems no reason to doubt that the upper pan is more recent than the lower zone of iron accumulation.

Morphologically the profiles at Goodland A and Torr are similar. It is therefore reasonable to suggest that the upper iron pan at Goodland A (and also at Goodland B) developed at the base of cultivation.

The length of time taken for the upper pan at Torr to form can be calculated within fairly narrow limits. Evidence from maps and documents indicates a scanty population in this area in the late eighteenth century and the rapid growth in both population and settlement prior to the Irish Famine of the 1840's (Evans, 1956, pp. 232–3). By the time of the Second Ordnance Survey in the late 1850's many dwellings had already been abandoned and the area cultivated had been drastically reduced. In this area which is marginal for cultivation it is unlikely that the abandoned field from which the soil profile has been described was

cultivated for long after the Famine. A reasonable estimate for the length of time taken for the formation of the upper pan is 100 years.

Goodland: Soil History and Chronology

It is now possible to suggest the history of soil development at Goodland and to establish a chronological framework for it.

The neolithic pits were sealed by the upper pan which must therefore date from post-neolithic times. The lower zone of iron accumulation can reasonably be regarded as the result of gradual leaching of the soil between the time temperate climatic conditions were established after the final retreat of the Quaternary ice and the clearance of the area by neolithic settlers. The upper part of the profile suggests that leaching and pan formation were more intensive in post-neolithic times than before. This might be explained by the cumulative effect of the progressive leaching and decalcification which had occurred by neolithic times, and by the intensification of these processes consequent upon the primitive neolithic cultivation of the area which cut through the tops of the ritual pits and scattered their contents over the whole site (full discussion in Proudfoot, forthcoming; Mitchell, 1953; Proudfoot, 1955; Pearsall, 1956). The depth of cultivation determined the position at which the upper iron pan developed. After cultivation ceased and the upper iron pan had formed, blanket bog grew over this area.

On the slopes of the grassland tillage continued after peat had formed over the neolithic site. Iron pan developed on many of these slopes but there was probably little bog formation on them until the early fields, marked by their banks and ditches, had fallen into disuse. In these fields an upper iron pan has formed at the base of cultivation and an intensely black humus layer A_H is found within the top few inches of the soil. This layer seems to be causing surface waterlogging and conditions favourable for the spread of *Juncus* and subsequent development of blanket bog (above, p. 192).

If this sequence of events and the concept of the sub-peat podzol being a fossil soil are accepted as correct, a chronological framework can be supplied. The establishment of a temperate climate and forest vegetation, that is, the transition from Pre-Boreal (pollen Zone IV) to Boreal (Zone V), can be dated in round figures to 7000 B.C. (Clark, 1957, p. 160). The C14 age of a peat sample from the base of the bog overlying the neolithic site at Goodland has been estimated at 4150 ± 200 years (*c.* 2200 B.C.) by the Physics Department, Trinity College, Dublin (Sample TCD/2). In view of this and of C14 dates from north-west England the neolithic site at Goodland should be dated to the third millennium B.C. Between the first clearance of the area by neolithic settlers for the establishment of their ritual site, and the formation of the blanket bog, time has to be allowed for (i) the use of the site for ritual purposes, (ii) abandonment of the site which was then partly destroyed by tillage. As this occurred more intensive leaching of the soil was initiated and iron pan was formed.

By analogy with the known history of pan formation at Torr there seems no reason to doubt that the iron pan at Goodland could have

formed inside several centuries at the most. Rough calculations based on the amount of iron moved and on the distance through which it has moved, or on the percentage of iron moved, suggest that the pans could have formed in similar lengths of time. There was therefore adequate time for podsol development at Goodland between neolithic times and the date of formation of the overlying peat, if neolithic activity in the area started early in the third millennium B.C. and the peat began to grow later in the same millennium.

While the blanket bog was developing on areas of thicker drift such as the hollow in which the neolithic site lay, podzolization was continuing on the grassland where the chalk was thinly covered with drift. When these slopes were laid out in a number of fields and were cultivated the formation of iron pan was interrupted, but pan again began to form at the base of cultivation when the fields were abandoned. It is probable that pan formation is still in progress. Concomitantly areas of *Juncus* and blanket bog have spread, and are still spreading although the failure of the bog to encroach seriously on any of the late medieval huts in the area suggests that the rate of bog growth has been small during the last few centuries.

Generalized Time Scale		
7000–3000/2500 B.C.	1. Development of soils from boulder clay, with some leaching and the formation of a zone of iron accumulation. Probably some forest growth, at least on the areas of deeper drift.	
3000/2500 B.C.	2. Neolithic forest clearance and the establishment of a ritual site where the deeper drift begins to thin out on the slope of the chalklands.	
	3. Abandonment of the ritual site which was then partly destroyed by tillage.	Initiation of more intensive podzolization consequent upon the neolithic occupancy of the area.
	4. Formation of iron pan on areas of deep drift, development of impermeable humus layer and waterlogged conditions on surface.	
2200 B.C. (C14 date Sample TCD/2)	Initiation of peat in such areas.	
	5. Utilization of the grasslands with periodic burning of vegetation (charcoal layers in bog). Tillage on the downland (? rolling of boulders on to bog surface). Establishment of fields.	Continued podzolization of soils not covered by peat. Interruption of podzolization in cultivated areas.
	6. Abandonment of fields.	Iron pan formation resumed at base of tillage.
A.D. 1500	7. Building of huts over field banks and ditches.	Podzolization continuing. Development of peat and consequent burial of field banks.
1700–1850	8. Establishment of present townland and field boundaries.	Burial by bog of some of the pre nineteenth-century townland boundaries.
A.D. 1950	9. Sheep-grazing.	Podzolization under grassland and bog formation continuing.

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THE APPLICATION OF SOIL MICROMORPHOLOGY TO FOSSIL SOILS AND OTHER DEPOSITS FROM ARCHAEOLOGICAL SITES

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Summary

In archaeological sites of Pleistocene and Postglacial age fossil soil horizons may be buried or form part of a composite soil profile when they may be either degraded or relic in nature. Since the A horizons of soils may be identified by their humus forms and the B horizon by their fabrics, both immature and mature fossil soil horizons may be identified and distinguished from man-made deposits such as occupation layers and ditch fillings. Thus, micromorphology can be used as a geochronological technique for supplementing the existing knowledge of the mild and cold phases of the Pleistocene and to a lesser extent of the Postglacial.

In mature fossil soils, since the fabrics of many B horizons are characteristic of certain soil types and are not altered by colluvial activity, it is possible to deduce something of the physiographic environment under which such fossil soil horizons were formed and, in particular, of the climate at the time of their formation. Thus, from composite soil profiles in archaeological sections, relic fabrics have been observed and the primary origin of such colluvially derived soil material deduced. From buried profiles in loess sections of Europe the occurrence of braunerde fabrics with *sol-lessivé* features confirms the other lines of evidence which suggest that the mild phases of the Pleistocene had similar climatic conditions and that these differ from those of today in the same area only in that the summers are today somewhat cooler and wetter.

Introduction and Aim of Investigation

ARCHAEOLOGICAL sites are usually formed by sedimentation processes, and whenever these are interrupted soils will tend to form on the land surface thus exposed. Fossil soil horizons are frequently buried by succeeding deposits, as in many loess sites in Europe and America, or they may form part of a composite profile resulting from more than one phase of weathering. If the fossil part of the profile was formed under temperate conditions during one of the mild phases of the Pleistocene, it may be called a degraded soil, and this contrasts with a relic soil which has formed under tropical conditions such as during the Tertiary. There are very few sites in Western Europe containing fossil soil material formed during the Antepenultimate Interglacial, but the fossil floral and faunal assemblages (Zeuner, 1937, 1945) suggest that this mild phase was similar to the other interglacials and interstadials and was temperate in character. It is possible, however, that the long continued and superposition of periods of weathering and soil formation may, in favourable sites, significantly alter the existing soil-forming processes and the morphology of the soil formed, but there is little evidence for this during the longest, continuous period of weathering, the Penultimate Interglacial. In Western Europe soils formed during this period are typically mull forest soils,

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podzols and chernozems. Thus, most Pleistocene soils are mature and well drained (Saint Pierre-les Elbeuf),* and they contrast with the usually immature soils of later age (Bronze Age—Canford Heath; Iron Age—Bury Hill; Roman Age—Towcester) which are easily confused with occupation layers and man-made ditch fillings in archaeological sites.

Man-made deposits and fossil soil horizons can be identified by their field relationship combined with physico-chemical analyses (Zeuner, 1945; Cornwall, 1954), but it was thought that these methods might be considerably refined by using micromorphological techniques. Kubiena (1938, 1948, and 1953) considers that the A horizons of soils may be recognized in thin section by their humus forms and that B horizons may be identified by their fabrics.† Although knowledge of soil micromorphology is rapidly increasing, it cannot yet be assumed that all soil types may be distinguished by their own particular fabrics. Thus, a study was made (Dalrymple, 1955) of the humus forms and fabrics of modern soils from many sites in Europe and Africa. Their comparison with fabrics already described by other authors suggests that certain soil fabrics are associated with certain soil types, even though each soil type may not necessarily be characterized by a particular fabric. For example, braunerde fabrics are frequently found associated with the B horizons of brown forest soils and may be distinguished from those associated with grey-brown podzolics and podzols. Similarly these three fabric types may be distinguished from those such as rotlehms, roterdes, and braunlehms which are characteristic of many B horizons of tropical and sub-tropical soils.

This knowledge may be applied to archaeological sites. By recognizing humus forms and soil fabrics, immature and mature soil horizons may be identified and distinguished from man-made deposits. In addition, if the fabrics of fossil B horizons are observed, the fossil soil types may, in many cases, be inferred. Since soil fabrics depend on climate, topography, parent material, and time, it is possible to infer something about the environment and, by comparison with similar modern soil types, to deduce something of the climatic conditions at the time of their formation. In this way it is hoped to confirm or help to establish the relative chronology of archaeological sites.

Micromorphological Identification of Fossil Soil Horizons and Man-Made Deposits from Archaeological Sections

1. *Buried soils*

(*a*) *Immature, buried soils.* Immature, buried soils of archaeological importance are generally of Postglacial age. One section studied was a part of trench II from the Roman site at Towcester,‡ and includes an immature buried soil which was formed during a minor phase of non-deposition during Roman times and is sealed by the Roman town wall.

* All sites mentioned in the text are fully described in the appendix.

† A soil fabric may be defined as 'the arrangement of the constituents of a soil in relation to each other' (Kubiena, 1938), and the nomenclature used in this paper is that of Kubiena (1953).

‡ This site has recently been excavated by Alexander.

In the top few inches of this fossil soil a well-developed mull-humus form was observed and, underneath this, ditch filling material of colluvial origin.

Another Postglacial site which contains an immature buried soil is Holborough in Kent. Here there is some 9 ft. of frost-weathered chalk rubble containing a 2-in. thick, dark black horizon some 6 ft. from the ground surface. From the field evidence this horizon was thought to represent soil material, and this was confirmed since several thin sections showed the spongy fabric characteristic of mull. This horizon, therefore, represents buried A-horizon material, though probably not *in situ* as the field evidence suggests colluviation.

(*b*) *Mature, buried soils.* In Europe most of the mature, buried soils which contain *in situ* archaeological implements are found in loess sites. One such site is Saint Pierre-les-Elbeuf, situated on a spur of the River Seine, near Rouen. Here, in the more maritime transitional areas of loess deposition, many of the minor phases are not expressed in the stratified sequence of deposits, and solifluction with the formation of *cailloutis* becomes important. Sections from four pits at this site have been described by Chédeville (1893), Zeuner (1945, 1952, 1956), and Bordes (1954), but that from the 'grande briqueterie de Chédeville' is the most important archaeologically since evidence from this section led Zeuner to suggest a local penetration of Upper Palaeolithic man to this region for a short period at the end of the first Interstadial of the Last Glaciation. The section has been described by Zeuner (1945) as comprising a Postglacial brown earth which rests on Younger Loess II and is followed in turn by a brown earth of the first Interstadial of the Last Glaciation; a fairly fresh Younger Loess I; *argile rouge* of the Last Interglacial; and finally at the bottom some 20 metres of completely weathered Older Loess.

Micromorphological study of this section showed that the fresh Younger Loess I and II both have a matrix of mineral grains of a uniform silt-size that are bound together by deep brown intergranular braces (Plate I (*a*)). An occasional cavity is lined by micro-crystals of calcite, but otherwise there are no secondary concretions and no mobile components. Thus, the fabric is completely stable and all the conducting channels and most of the cavities are empty. Similar intertextic fabrics, but without the cavity linings of calcite, have been observed in thin section of loess from Pegwell Bay in Kent and Bobbitt's Hole in Suffolk and from deposits of Younger Loess at Niedemendig in Germany and Achenheim in Alsace.

Thin sections of the Older Loess at Saint Pierre-les-Elbeuf all have elementary intertextic fabrics, but in addition contain many secondary deep brown flecks and rounded concretions of iron. Similar braunerde fabrics have been observed from Older Loess from other sites, for example at Ebbsfleet in Kent. Thus the morphological and petrological differences between Younger and Older Loess, which are recognizable in the field (Zeuner, 1956), are reflected in their micromorphology.

Macroscopically the B horizon of the modern soil at Saint Pierre-les-Elbeuf is characterized by strongly developed prismatic and blocky struc-

tures, and associated with these in thin section are numerous vertical cracks. In places these are lined with colloidal material deep yellow to red-brown in colour which occurs in thin lamellae and completely permeates the braunerde fabric to a depth of 2–3 mm. away from the cracks. In the interstadial soil and the *argile rouge* these features are greatly intensified, and many of the channels within their fabrics are lined, the cavities filled, and occasionally even the mineral grains are coated with colloidal material* (Plate I (*b*)). In consultation with Professor Kubiena it was decided, provisionally, to call these fabrics containing mobile components within a braunerde matrix—braunerde fabrics with *sol lessivé*.† Similar fabrics have been observed from the B horizons of buried soils in loess profiles of Last Interglacial age from Achenheim and Ebbsfleet and from a series of deposits of Penultimate Interglacial age at Penfold's Pit, Slindon (Dalrymple, 1958).

It was thought that the physico-chemical properties of loess might on weathering give rise to *sol-lessivé* features, but more recently further thin sections have been studied and it has been shown that many of the B horizons of the present-day soils formed on the valley brickearths in Kent, as for example at Wingham, have similar fabrics, with spongy fabrics characteristic of mull in their A horizons and intertextic or braunerde fabrics in their C horizons. These braunerde fabrics with *sol lessivé* show close similarities with those described by Altemüller (1956) and Kubiena (1956) from the B horizons of parabraunerdes formed on loess in north Germany and from a similar group of soils in Belgium described by Laruelle (reported by Brewer (1957)). These fabrics also show affinities to those described by Frei and Cline (1949) from the B horizons of grey-brown podzolic soils from America, but here the additional mobile material is well orientated and occurs as thick bands differing in colour. Whilst the relationship of braunerde fabrics to those containing *sol-lessivé* features is not fully understood, the present evidence suggests that braunerde fabrics containing *sol-lessivé* features show more affinities with the grey-brown podzolic fabrics than with the braunerde fabrics and are more frequently associated with grey-brown podzolic soils than with brown forest soils.

2. *Degraded soils*

Degraded soils containing *in situ* archaeological implements are seldom observed, but Zeuner (1954) has described a site from Spanish Morocco which contains Mousterian and Upper Palaeolithic material. Here at Cabo Negro a composite soil profile is developed on gneiss with rotlehm fabrics beneath those of a meridional braunerde. In thin section the 'spotted-rotlehm zone' contains a highly mobile groundmass which is light yellow in colour and has been partly eroded. In

* These observations may well account for the redness of the *argile rouge* which has been noted by many authors and which suggested to Zeuner (1945, p. 75) that it was 'reminiscent of the Mediterranean variety of this [brown-earth] soil'.

† The use of *sol lessivé* for this specific micromorphological phenomenon and of braunerde fabric with *sol lessivé* as a fabric term is in some ways unfortunate and the nomenclature relating to these features is under review.

addition there is orange red, iron-stained colloidal material in many of the conducting channels and around a few mineral grains. The process of eluviation of the mobile ground-mass has gone a stage farther in the horizon underneath, the 'spotted-rotlehm zone'. Here, the light yellow ground-mass is still present, but only in localized areas and in a few old conducting channels, and most of the matrix is now permeated by deep-red colloidal material which coats the mineral grains and fills most of the cavities.

This degraded profile was chosen and described in detail because the fabrics of these two horizons illustrate how a mobile ground-mass may be eluviated from one horizon and washed into a lower horizon. The character of this process of illuviation is different from the eluviation of a rotlehm profile with the formation of Iwatoka precipitates described by Kubiena (1954), and it is thought that the process described above may be similar to that giving rise to the *sol-lessivé* phenomena mentioned earlier.

3. *Relic soils*

Many archaeological sections of Pleistocene age contain colluvially derived relic-soil material. For example at Penfold's Pit, Slindon, over 7 ft. of solifluction deposits are exposed and in thin section show rotlehm fabrics. Similar fabrics have been observed from other archaeological sites, and since such soil fabrics today are only observed from *in situ* tropical soils these fossil soil horizons must be derived from weathered products formed prior to the first glacial phase and probably during the Tertiary.

In south-eastern England Pliocene deposits, Clay with Flints and plateau brickearths are all preserved in discontinuous patches on the summits of the Chilterns and North Downs and it was thought that the head at Penfold's Pit might be derived from these deposits. Numerous sections have been studied and many rotlehm fabrics observed. Weathered Pliocene deposits from Headley Heath and Box Hill have rotlehm fabrics as have Clay with Flints in Hertfordshire and various sites in Kent, whilst in plateau brickearths many of those studied have rotlehm fabrics at depth, but podzolic fabrics nearer the surface, and at the surface a mull or moder humus form. Thus it would seem that the head at Penfold's Pit has been derived by solifluction from relic weathered products like Clay with Flints or plateau brickearths.

Another archaeological site containing relic material is Tornewton Cave* in Devon. The section outside the cave has produced an enormous quantity of animal bones and a few blades of Upper Palaeolithic appearance. At the base of the section is a deposit of red clay, which in thin section has a terra-fusca fabric similar to that observed from red-soil material resting on and penetrating into the Devonian limestone plateau near Tornewton.

* Recently excavated by Zeuner and Sutcliffe.

4. *Man-made deposits*

The application of micromorphological techniques to deposits formed by man's activity has not yet been developed to any great extent, but the identification of humus forms distinguishes the A horizon of a soil from a habitation level. Ditch or barrow fillings frequently contain foreign materials such as splinters of flint or bone in Palaeolithic sites (Tornewton), whilst fragments of pottery, charcoal, or carbonized seeds are often found in later sites. In addition, widely contrasting fabric elements are often juxtaposed in ditch fillings (Towcester).

Some Environmental and Chronological Deductions from the Fossil Soil Horizons and Man-Made Deposits Identified

Mature fossil soils are generally found in Pleistocene archaeological sections, and their identification by means of their fabrics frequently allows the soil type to be inferred. This is the case with buried soils from loess sites in south-eastern England, northern France, and north Germany. Sections from these sites include Older Loess and Younger Loess as well as modern and fossil soil horizons. Their micromorphological identification (Younger Loess, intertextic fabrics, Older Loess, braunerde fabrics, modern and fossil B horizons, braunerde fabrics, and braunerde fabrics with *sol lessivé*) helps to confirm the relative chronology of these sites. The widespread occurrence of braunerde fabrics with *sol-lessivé* phenomena in interglacial and interstadial soils suggests that the climatic conditions of the mild phases of the Pleistocene cannot have differed markedly from one another.

Mention has already been made that braunerde fabrics with *sol lessivé* are thought to be associated more with grey brown podzolics than with brown forest soils, and this fact may well explain why in many loess sites *sol-lessivé* features are more marked in the fabrics of the buried soils than of the *in-situ* soils. At Ebbsfleet there are no *sol-lessivé* features in the modern soil, and its B horizon has a typically braunerde fabric. The presence and distribution of these soil fabrics seem not to be due to the length of time available for soil formation, nor to more than one phase of *in-situ* weathering, but rather they reflect a minor climatic difference in the Postglacial as compared to the mild phases of the Pleistocene. The inference would be that the summers during at least a part of the mild phases of the Pleistocene were somewhat warmer and drier than today and this is in agreement with that already known of the fossil flora and fauna and from soil analyses (Zeuner, 1937 and 1945).

Mature fossil soils found in degraded profiles may also indicate climatic conditions. At Cabo Negro the identification of rotlehm fabrics beneath meridional braunerde fabrics suggests a change in climatic conditions. On archaeological evidence (Zeuner, 1954) the rotlehm is assigned to the first Interstadial of the Last Glaciation and the meridional braunerde to the Postglacial. Thus, it would seem that at Cabo Negro the climate was somewhat warmer during the Interstadial than today.

The micromorphological identification of colluvially derived relic-soil material in archaeological sections does not necessarily give any direct

evidence for the climatic conditions at the time of its derivation in the Pleistocene, since the fossil fabric only indicates the conditions of its primary formation. If, however, the incorporation of the relic-soil material results from solifluction, as in the case of the head at Penfold's Pit and the red-clay at Tornewton Cave, a cold phase of the Pleistocene is indicated. In contrast, incorporation by soil creep and other similar processes suggests a cool, moist phase. In addition the indirect evidence from thin sections of relic-soil material often indicates from what deposits it has been derived. Thus, in the head from Penfold's Pit the occurrence of rotlehm fabrics suggested derivation from Pliocene deposits, Clay with Flints or possibly plateau brickearths and in the red-clay horizon at Tornewton Cave from terra fusca soil material (itself probably a relic formation) on the Devonian limestone plateau.

The identification of, and distinction between, sedimentary man-made deposits and immature soil horizons by means of humus forms and the presence of foreign materials and fabric elements indicate little about the environment in which they were deposited. It is, however, possible to infer something of the vegetation at the time of the formation of immature, buried soils from their humus forms, and their occurrence in Pleistocene and early Postglacial sections means that moist temperate climatic conditions were prevalent. Such immature soil horizons indicate stable conditions and often form on, and are buried by, colluvial material, as at Holborough. Here the colluvial material is likely to represent a cooler or moister phase, though in later sites man is probably the dominant agent in the formation of colluvial horizons in archaeological sections. In these later sites the fossil soil horizons represent periods of non-occupation of the site in contrast to the man-made deposits.

In this way the micromorphological identification and distinction between immature, fossil soil horizons and man-made horizons from archaeological sections may be used as a geochronological technique, and in Pleistocene and early Postglacial sites may indicate something of the environment and climatic conditions at the time of their formation.

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APPENDIX

ALPHABETICAL list of all the sites mentioned in the text giving the sequence of deposits and types of fabrics observed. Sites which have been mentioned but not studied in detail are indicated by an asterisk.

ACHENHEIM,* Alsace.
Younger Loess—intertextic.
Older Loess—braunerde with *sol lessivé.*
Complete section, Zeuner, 1953.

BOBBITT'S HOLE, near Ipswich, Suffolk.
Loess deposited in water—intertextic.
Spencer, 1953.

BOX HILL, near Dorking, Surrey.
30–45 cm. Pliocene material (?)—rotlehm. — Relic.

BURY HILL,* Hampshire.
Brown earth. — Buried.
Iron Age. — Pgl.
Zeuner, 1941.

CABO NEGRO, Tetuan, Spanish Morocco.
Meridional braunerde and rotlehm. — Degraded.

(i)	0–20 cm.	'bleached horizon'	—meridonal braunerde.	Pgl.
(ii)	20–70 cm.	'transition to rotlehm'		
(iii)		'rotlehm'	rotlehm.	L.$Gl_{1/2}$
(iv)	70–370 cm.	'spotted rotlehm zone'		
(v)		'rotlehm with stones'		
(vi)	370 cm.	gneiss		

Zeuner, 1954.

CANFORD HEATH,* Hampshire.
Podzol. — Buried.
Bronze Age. — Pgl.
Cornwall, 1954.

CHRISTMAS COMMON, Hertfordshire.
Rotlehm. — Relic.
25–35 cm. Clay with Flints—rotlehm.

EBBSFLEET, Kent.
Intertextic, braunerde, and braunerde with *sol lessivé*. — Recent and buried.

(i)	0–8 in.	A horizon—mull.	Pgl.
(ii)	8 in.–1 ft.	B horizon—braunerde.	
(iii)	1 ft.–3 ft.	C horizon—calcareous hillwash.	L.Gl.
(iv)	3 ft.	C horizon—calcareous hillwash.	
(v)	8 ft.	B horizon—braunerde with *sol lessivé*.	L.Igl.
(vi)	8 ft. 6 in.	B horizon—braunerde with *sol lessivé*.	
(vii)	9 ft.	B horizon—braunerde with *sol lessivé*.	
(viii)	9 ft. 6 in.	C horizon—Older Loess—braunerde.	P.Gl.
(ix)	11 ft.	C horizon—Older Loess—braunerde.	

Lower Palaeolithic.
Burchell, 1933 and 1935, and Zeuner, 1945 and 1952.

HEADLEY HEATH, Surrey.
Rotlehm.
2 ft. 6 in. Red weathered Pliocene material—rotlehm.

HOLBOROUGH, Snodland, Kent.
Rendzina. — Buried.
(1) 3 ft. 6 in.–3 ft. 9 in. C horizon—frost weathered chalk solifluction material.
(2) 4 ft. 0 in.–4 ft. 1 in. C horizon—grey stained chalk solifluction material.
(3) 4 ft. 1 in.–6 ft. 0 in. C horizon—chalk solifluction with $CaCO_3$ concretions.

(4) 6 ft. 0 in.–6 ft. 2 in. A horizon—black humus horizon —mull.
(5) 6 ft. 2 in. C horizon—chalk solifluction with $CaCO_3$ concretions.

Burchell, unpublished.

NIERDERMENDIG, Germany.
Fresh Younger Loess—intertextic.
Zeuner, unpublished.

PEGWELL BAY, Cliffsend, Kent.
Intertextic and braunerde with *sol lessivé*. — Recent and buried.
0–16 cm. A horizon—mull.
16–121 cm. B horizon, weathered loess—braunerde with *sol lessivé*.
121–249 cm. C horizon, fresh loess—intertextic.
249–399 cm. Thanet Beds.
Pitcher *et al.*, 1954.

PENFOLD'S PIT, Slindon, Sussex.
Brodel soil, braunerde with *sol lessivé* and rotlehm. — Recent, buried, and composite.

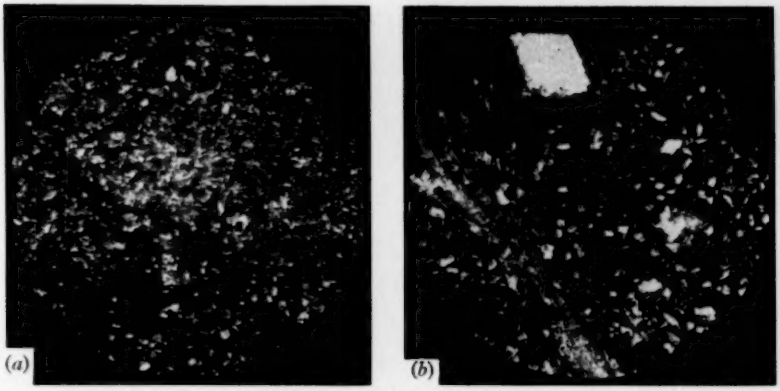
(i) 0–6 in.	B horizon—braunerde.	Pgl.
(ii) 6 in.–2 ft. 0 in.	Structure rawmark.	Cold phase of L.Gl.
(iii) 2 ft. 0 in.–3 ft. 6 in.	Head—rotlehm.	P.Gl.
(iv) 3 ft. 6 in.–4 ft. 0 in.	Lens of silt—loam—braunerde with *sol lessivé*.	
(v) 4 ft. 0 in.–5 ft. 3 in.	Head—rotlehm.	P.Gl. (?)
(vi) 5 ft. 3 in.–6 ft. 9 in.	Raft of silt—loam—braunerde with *sol lessivé*.	
(vii) 6 ft. 9 in.–7 ft. 6 in.	Head—rotlehm.	P.Gl. (?)
(viii) 7 ft. 6 in.	Talus.	

Acheulian.
Dalrymple, 1958.

SAINT PIERRE-LES-ELBEUF, near Rouen, France.
Braunerde with *sol lessivé*, intertextic and braunerde. — Recent and buried.
Pit I, 'grande briqueterie de Chédeville'.

(i) Removed.	
(ii) B horizon—braunerde with *sol lessivé*.	Pgl.
(iii) C horizon—Younger Loess II—intertextic.	$L.Gl_2$.
(iv) A horizon—mull.	
(v) B horizon—braunerde with *sol lessivé*.	$L.Gl_{1/2}$.
(vi) B/C horizon—braunerde with *sol lessivé*.	
(vii) C horizon—Younger Loess I—intertextic.	$L.Gl_1$.
(viii) B horizon—braunerde with *sol lessivé*.	L.Igl.
(ix) C horizon—Older Loess—braunerde.	
(x) B horizon—braunerde with *sol lessivé*.	L.Igl. (?)
(xi) B horizon—braunerde with *sol lessivé*.	
(xii) C horizon—Older Loess—braunerde.	P.Gl. (?)
(xiii) C horizon—Older Loess—braunerde.	

Upper Palaeolithic.
Zeuner, 1945.



(*a*) Thin section under doubly polarized light (× 50) of Younger Loess II from the 'grande briqueterie de Chédeville' section at Saint Pierre-les-Elbeuf showing silt-sized mineral grains, empty cavities, and intergranular braces of the intertextic fabric

(*b*) Thin section under doubly polarized light (× 50) of the B horizon of the buried soil ($L.Gl._{ig}$) from the 'grande briqueterie de Chédeville' section at Saint Pierre-les-Elbeuf showing the variation in grain size, flecks and concretions of iron and intergranular braces typical of braunerde fabrics. Superimposed on this is a conducting channel filled with deep yellow, colloidal material showing flow structure—braunerde fabric with *sol lessivé*

J. B. DALRYMPLE—PLATE I

TORNEWTON, Torbryan, Devon.

Terra fusca. — Relic.

(A) *Plateau site*

(i) 0–3 in. — A horizon—mull.
(ii) 3–8 in. — B horizon—terra fusca.
(iii) 8 in.–1 ft. 6 in. — B horizon—terra fusca.
(iv) 1 ft. 6 in.–2 ft. 0 in. — B horizon—terra fusca.
(v) 2 ft. 0 in. — C horizon—Devonian limestone.

(B) *Section outside cave*

(i) Tip.
(ii) Black soil—mull—rendzina.
(iii) Limestone rubble.
(iv) Transition horizon.
(v) Reindeer stratum.
(vi) Elk stratum.
(vii) Head.
(viii) Red clay—terra fusca.

Zeuner and Sutcliffe, unpublished.

TOWN WALL, Towcester, Northamptonshire.

Immature soil. — Buried.

Trench II, sealed under Bank of Town Wall.

(i) Top 6 in. — A horizon—mull.
(ii) Middle 6 in. — C horizon—filling material.
(iii) Lower 6 in. — C horizon—filling material.

Roman.

Alexander, unpublished.

WHITE HILL, Near Wye, Kent.

Podzolic—rotlehm. — Recent—relic.

(i) 0–1·5 in. — A_1 horizon—dark grey brown organic loam—moder.
(ii) 1·5 in.–4 in. — A_2 horizon—brown loam—podzolic.
(iii) 4–15 in. — A_2/B horizon—yellowish-brown fine sandy loam—transitional podzolic to rotlehm.
(iv) 15–26 in. — B horizon—lighter yellowish-brown fine sandy loam—transitional rotlehm to podzolic.
(v) 26–60 in. — B/C horizon—yellowish-red fine sandy clay loam—rotlehm.

Askew, unpublished.

WINGHAM, Kent.

Intertextic and braunerde with *sol lessivé*. — Recent on brick-earth.

(i) 0–8 in. — A horizon—mull.
(ii) 8–12 in. — A/B horizon—braunerde (subsidiary *sol lessivé*).
(iii) 12–37 in. — B horizon—braunerde with *sol lessivé*.
(iv) 37–66 in. — C horizon—intertextic.

A SEQUENCE OF BEECHWOOD SOILS ON THE CHILTERN HILLS, ENGLAND

B. W. AVERY

(*Soil Survey of England and Wales*)

Summary

The chalk and associated superficial deposits of the Chiltern Hills give rise under beechwoods to a sequence of soils ranging from rendzina through brown earth (*sol lessivé*) to podzol, closely paralleled in developmental sequences established elsewhere on uniform calcareous materials. The salient features of the genetic soil types represented are described and their evolution discussed in relation to vegetation and site characteristics. On base-deficient soils, mor formation under beech is conditioned by local climatic factors and management practices as well as by inherent fertility variations and is only associated with advanced podzolization on appreciably sandy materials. On silty plateau soils with imperfect drainage, 'micro-podzols', which may be transitory, are formed.

THE ecological classification of British beechwoods given by Tansley (1949) is based to a considerable extent on Watt's (1934) detailed study of the extensive semi-natural woods on the Buckinghamshire and Oxfordshire Chilterns. These woods, traditionally managed by selection and natural regeneration, are associated with a sequence of soils ranging from shallow rendzina on chalk to strongly acid and locally podzolized loams on Clay-with-flints and allied superficial deposits. In this paper the morphology, composition, and geographic distribution of the soil types represented are outlined and their evolution discussed in relation to vegetation and site characteristics.

Soil-forming Factors

Physical features and geology

The Chiltern Hills constitute a chalk cuesta, modified by sub-aerial and marine planation (Wooldridge and Linton, 1955). From the indented scarp overlooking the Vale of Aylesbury, which rises to 750–850 ft. O.D., the dip-slope plateau, scored by numerous dry valleys, falls gradually south-east towards the London basin. Tributaries of the Thames and Colne rise in the principal valleys, dry continuations of which intersect the scarp by way of broad 'wind-gaps' at Princes Risborough, Wendover, and Tring (see Fig. 1).

On the plateau surface, the underlying Chalk is everywhere obscured by Clay-with-flints or 'Pebbly Clay and Sand', enclosing lenses of gravel and brick-earth and representing the weathered remains of Chalk and Tertiary formations, disturbed and redistributed by solifluxion or ice-action (Sherlock, 1947). The scarp face and the steeper valley sides are virtually drift-free, but the dry-valley floors and foot-slopes are covered by more or less decalcified, flinty solifluxion (Coombe) deposits, passing locally into roughly sorted flint gravel. Where undisturbed by recent erosion, the superficial layers of both plateau and valley drift are rich in silt (2–50μ) and probably incorporate loessial additions (cf. Perrin, 1956).

Climate

The climate is sub-oceanic, with a mean annual temperature range of about 24° F. (January 37° F.; July 61° F.) and annual rainfall averaging 30 in. Potential evapo-transpiration, amounting annually to about 18 in. (Penman, 1950), normally exceeds rainfall from April to September inclusive.

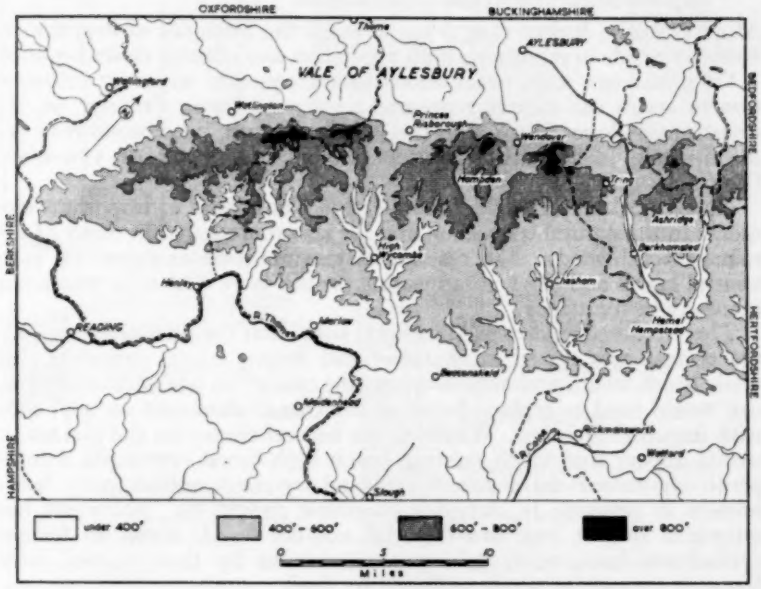


FIG. 1. Physical features of the Chiltern Hills.

Vegetation

Woods occupy about 18 per cent. of the Buckinghamshire and Oxfordshire Chilterns, and apart from recent plantations, are predominantly high-forest dominated by beech. A little east of the Hertfordshire border, both the proportionate extent of woodland and the dominance of beech decline, existing woods being chiefly of oak standards with hazel or hornbeam coppice.

Semi-natural vegetation other than woodland is represented on the escarpment by chalk grassland and scrub, and on the plateau by numerous commons, dominated by acidic grassland or bracken, or occasionally by *Calluna*. The widespread invasion of former sheep-walks and commons by woody vegetation enabled Watt (1934) to elucidate the course of natural succession. Two seres (hawthorn and juniper) were recognized on the escarpment and four (A_0, A, B, and C) on the acid loams of the plateau, each related to soil variations, and each culminating in

characteristic beechwood associations, later grouped by Tansley (1949) as follows:

Fagetum calcicolum: beechwoods on chalky soils, including sanicle and mercury types.

Fagetum rubosum: beechwoods on non-calcareous loams characterized by a *Rubus* field layer.

Fagetum ericetosum: beechwoods on podzolized loams and sands with impoverished, acidophile ground-flora.

More recently, Brown (1953) has stressed the influence of exposure to westerly winds in modifying both vegetation and edaphic characteristics.

On calcareous soils, beechwoods have frequently arisen by colonization of scrub and clearly represent a natural climax, although on the driest chalk slopes exposed to the west and south, beechwood may fail to maintain itself, yielding place to xerophile scrub or yew-wood (Bourne, 1931).

On non-calcareous soils, both ash and oak appear as important elements in the natural succession and are also represented in many of the mature beechwoods. Ash reaches its maximum development on subneutral loams and clays, disappearing on the more acid soils where oak increases in frequency.

There is some evidence (Mansfield, 1952) that the primitive forest on the plateau was mixed in character and Brown (1953) considers that while beech would probably dominate the canopy on well-drained loams, oak would tend to replace beech as the climax-dominant on acid soils with impeded drainage. Whatever the natural climax on the plateau, it would appear that much existing beech high-forest represents a comparatively recent development, induced by nineteenth-century landowners in response to changing economic conditions. Mansfield has estimated that at least one-third of existing woods stand on former agricultural land, while others, as evidenced by their names, were formerly coppice or scrub exploited for fuel.

Types of Soil Formation

Soils of three major genetic types, rendzina, brown earth, and podzol, have been recognized in the Chiltern woods, together with profiles of transitional character, to be described as brown calcimorphic (rendziniform) soils and podzolic soils respectively. Fig. 2 shows the salient features of these profile types, represented as members of a continuous morphological sequence. As in the classification scheme adopted by Duchaufour (1956), weathered superficial deposits like Clay-with-flints, that incorporate 'fossil' soil material of ***braunlehm*** or ***rotlehm*** character (Kubiena, 1953), are considered as 'parent materials' which when exposed at the surface may give rise to profiles of varying genetic type in conformity with contemporary environmental factors.

For soil-survey purposes, the woodland soils have been grouped with their agricultural counterparts as soil series, primarily on a parent-material basis. The geographic distribution of the principal soil series and their relation to genetic soil types is indicated by Fig. 3, which shows a generalized cross-section of a typical dry valley. Since these valleys are

usually asymmetrical (Ollier and Thomasson, 1957), calcimorphic soils are more extensive on south- and west-facing slopes than on those exposed to the north and east, which are in general less steep and are often continuously mantled by thin solifluxion deposits.

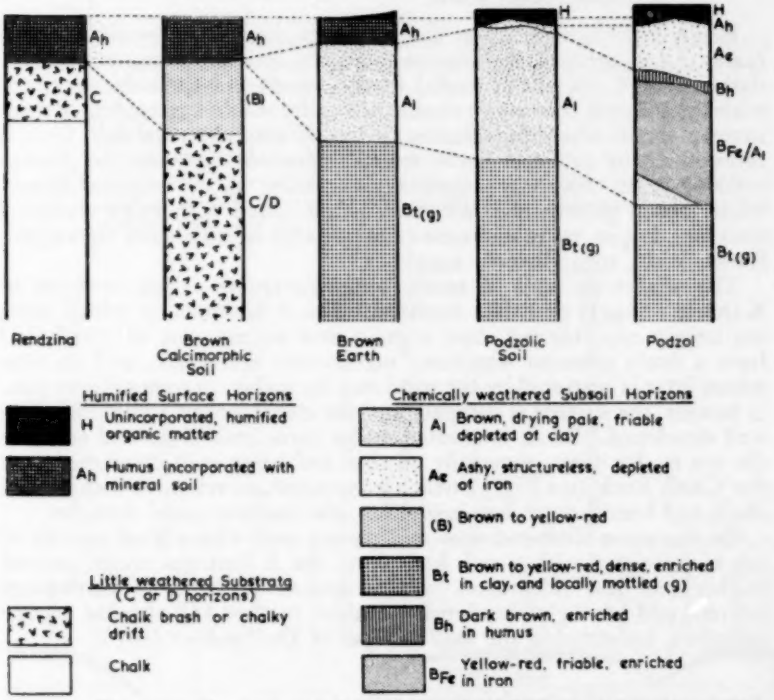


FIG. 2. Diagrammatic representation of genetic soil types as members of a sequence. (Horizon nomenclature after Scheffer-Schachtschabel, 1956. Lehrbuch der Agrikulturchemie und Bodenkunde, Enke, Stuttgart.)

The analytical data given in Table 1 relate to representative profiles on sites which, judging by existing maps and records, have carried woodland or scrub for at least 200 years.

Rendzinas

Typical rendzinas with AC profiles, grouped for survey purposes with the Icknield series, are virtually confined to the scarp zone and to steep convex slopes bordering the deeper valleys. The following is a representative profile description:

L Thin litter resting directly on mineral soil.

A (4–6 in. thick) Very dark greyish-brown,* friable, humose loam containing numerous chalk fragments; well-developed granular structure; clear boundary.

* Munsell colour names are used in profile descriptions.

A/C (3–9 in. thick) Brown-stained chalk brash set in a matrix of pale brown chalky loam, with irregular penetration of humus; roots much less frequent.

C On fissured and fragmented chalk with brownish stains, becoming harder and more massive below.

Beech litter breaks down comparatively rapidly on rendzinas as a result of free aeration and intense biological activity, giving rise to very dark-coloured calcium-saturated humus which is intimately associated with the mineral fraction in characteristically stable aggregates. Except in deep shade, where ivy (*Hedera*) is locally dominant, the field layer is represented by calcicole herbs, notably *Sanicula europaea* and *Mercurialis perennis*. *Sanicula* is generally dominant on dry exposed slopes, while strong growth of *Mercurialis* is associated with more sheltered sites and deeper, more moisture-retentive soils in which ash regenerates freely (Watt, 1934; Brown, 1953).

The shallowest soils of south- and west-facing slopes conform to Kubiena's (1953) mull-like rendzina. The A horizons, in which roots are largely concentrated, may contain over 60 per cent. of Chalk and have a finely granular structure; earthworms are scarce, and on sites where litter is scattered by the wind and the soil is correspondingly poor in humus, the surface is compact and the characteristic structure is less well developed. Beech is stunted under these conditions and tends to die out in dry years, especially on thin and stony soils developed over the 'Chalk Rock' (see Fig. 3), which is less moisture-retentive than normal chalk and breaks down less easily into silt- and clay-sized particles.

On the more sheltered sites and deeper soils where good growth of ash is associated with a rich herb flora, the A horizons are in general thicker and less calcareous, with abundant evidence of earthworm activity and strongly developed granular to fine sub-angular blocky structure, constituting the *mull calcique* of Duchaufour (1956).

Brown calcimorphic (rendziniform) soils

This term has been applied to near-neutral (pH H_2O 6·0–7·5) soils with calcium-rich mull humus, distinguished from typical rendzinas by the appearance of a brown or reddish (B) horizon (see Fig. 2), originating either by weathering *in situ* or as transported material. These soils, common on moderate (8–15°) slopes, are associated with colluvial or solifluxion deposits containing varying proportions of loess-like loam and earlier-formed Clay-with-flints mixed with fragmented chalk. Complete leaching of carbonates, followed by progressive acidification of the upper horizons, is accompanied by the development of thinner and less strongly aggregated A_h horizons and by indications of clay migration, leading to the gradual differentiation of a textural B horizon. According to Duchaufour (1956), clay-humus complexes formed in calcium-saturated soils are strongly flocculated and resistant to microbial decomposition, but with the development of an acid reaction, less stable and more easily dispersed complexes are formed, humus accumulates in smaller amounts, and translocation of fine clay is thereby facilitated.

Brown calcimorphic soils of the Coombe series (see Fig. 3), located on sheltered footslope sites where the tendency to decalcification is inhibited by soil creep and animal activity, are typified by the following generalized profile description.

L Thin litter resting directly on mineral soil.

A (4–6 in. thick) Very dark greyish-brown, friable, silty clay loam containing small, shattered flints and chalk fragments; well-developed granular to fine sub-angular blocky structure; clear boundary.

(B) (5–12 in. thick) Brown, friable, flinty silty clay loam with chalk fragments and darker-coloured infillings; moderately well-developed fine sub-angular blocky structure; merging boundary.

C On rubble of brown-stained chalk lumps and small shattered flints set in a matrix of pale brown, porous, chalky loam; compact in place, but friable when dug out.

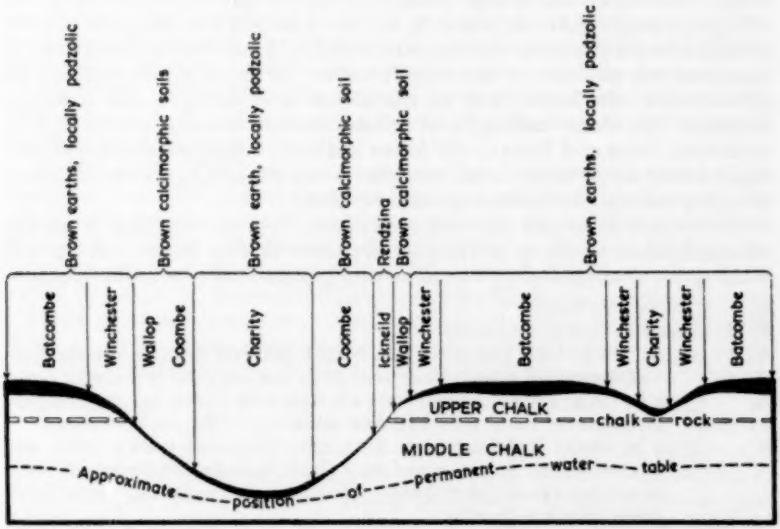


FIG. 3. Schematic cross-section of a typical dry valley, showing the topographic relationships of soil series and genetic soil types.

These soils are more moisture-retentive than chalk-rendzinas and generally support beech of superior quality; calcicole herbs are abundant in the field layer, and gaps left by felling are freely colonized by ash.

Soils of the Wallop series, associated with thin, disturbed relics of Clay-with-flints on upper valley sides and spurs, show a similar succession of horizons, but are finer in texture, and often very flinty, with (B) horizons of strong brown to yellowish-red, finely blocky, plastic clay as in Kubiena's (1953) *Terra fusca*. Where sited on exposed brows, these soils are often decalcified, even with chalk at 12 in. or less, and show a strong tendency to textural differentiation (see profile Bu 17, Table 1).

Brown earths

Leached mull soils associated with *Fagetum rubosum* are characterized on both plateau and valley drift by brown, friable sub-surface horizons, designated A_1, succeeded by denser and finer-textured B_t horizons with polyhedral or blocky structure (see Fig. 2). In this respect, they resemble the French *sols lessivés* (Duchaufour, 1956) and certain American 'podzolic' soils (Lyford, 1952) rather than normal *braunerde* which according to Kubiena (1953) have A(B)C profiles of uniform texture. In Britain, following Robinson (1949), leached brown soils of this kind, developed on calcareous sediments or on deeply weathered drift deposits of *braunlehm* character, have generally been classed as brown earths or brown forest soils so long as the humus remains of mull type and little or no differential eluviation of sesquioxides can be identified. The leached sub-surface horizons, though relatively pale coloured when dry, have a *braunerde*-like fabric distinct in colour and structure from the ash-grey, single-grain or platy A_e horizons of podzols, and the characteristic texture profile is not associated with any consistent change in the chemical composition of the clay fraction. In the Chiltern profiles on plateau drift the lower limit of the solum is ill defined, and although oriented 'clay skins' indicative of colloid movement occur as coatings on structural faces and flints in the lower horizons, mechanical and mineralogical analyses to be reported in a subsequent publication have confirmed that depositional variations are also involved.

Brown earths of the Charity series (see Fig. 3), resulting from the decalcification of flinty solifluxion deposits in the larger valleys and wind-gaps, are typified by the following generalized profile description.

L (Up to 2 in. thick.)
F, H Absent or feebly developed.
A_h (2–4 in. thick) Dark greyish-brown, friable, flinty silt loam with moderately well-developed crumb structure. Clear but irregular boundary.
A_1 (5–12 in. thick) Brown, friable, flinty silt loam with weakly developed crumb structure; soft and paler in colour when dry. Merging boundary.
B_t (9–24 in. thick) Reddish-brown, firm, flinty silty clay loam to silty clay becoming finer in texture and more plastic with depth; moderately well-developed sub-angular blocky to blocky structure with clay skins; black manganiferous deposits.
C On heterogeneous pale brown to reddish-yellow chalky drift containing numerous chalk fragments and shattered flints.

Profiles free of carbonates to depths greater than 3–4 ft., occurring in some of the dry valley bottoms, appear to have developed from superposed materials of colluvial or fluviatile origin which may have been non-calcareous when deposited.

While the valley soils are normally well drained, brown earths of the Batcombe series, developed on level or gently sloping plateau sites where the drift is thick, have mottled subsoils indicating transition to the surface-water gley or *pseudogley* (Kubiena, 1953) type. The following generalized profile description is typical.

L (Up to 2 in. thick).
F, H Absent or feebly developed.

A_h ($1\frac{1}{2}$–3 in. thick) Very dark grey to greyish-brown, friable silt loam with a moderately well-developed crumb structure and occasional small flints. Clear but irregular boundary.

A_1 (7–15 in. thick) Yellowish-brown, friable silt loam containing small shattered flints; weakly developed crumb structure; light yellowish-brown and soft when dry; locally paler in colour and structureless towards lower limit. Merging boundary.

B_t/g (18–24 in. thick) Strong brown to yellowish-red, firm, flinty silty clay to clay, faintly to distinctly mottled with paler and with redder colours; moderately well-developed sub-angular blocky to blocky structure with clay skins; ill-defined boundary.

On similar material, prominently mottled with red, pale brown and grey, the grey colours commonly associated with very plastic clay coating flints, fissures and root-paths; structure more massive, weakly prismatic to blocky.

The silty upper horizons of these soils, often containing relatively few small flints, are considered to have developed from a loess-like superficial deposit, more or less incorporated with the underlying Clay-with-flints by solifluxion. On parts of the dip-slope plateau below about 650 ft. O.D., where the drift contains varying proportions of sand and flint pebbles, both soil and subsoil are locally coarser in texture, but silt loams predominate on level sites.

At the edges of ridges and on spurs, the A horizons become more flinty and less silty, and as the slope increases and the drift thins out, the subsoil clay becomes increasingly tenacious and more uniformly reddish in colour. In the soils grouped as Winchester series (see Fig. 3), the irregular chalk surface, normally encountered at depths ranging from 15 in. to 5 or 6 ft., is overlaid by extremely plastic clay, enclosing large nodular or broken flints, and often blackened by manganiferous deposits. This clay, representing the *argile à silex sensu stricto* of Brajnikov (1937), probably consists largely of chalk-residue, more or less concentrated by illuviation.

In each of the above series, modal brown earths have A_h horizons 2–4 in. thick with a soft crumb structure and C/N ratio 12–15—the *mull forestier* of Duchaufour (1956)—and are associated with woods of Watt's (1934) sere A, corresponding to Brown's (1953) *Asperula type*, which often contain some ash and in which optimum height-growth of beech has been recorded. Except in dense shade, the field layer is dominated by luxuriant *Rubus*, accompanied locally by a variety of herbs, including *Galeobdolon luteum*, *Circaea lutetiana*, and *Asperula odorata*, believed to be exacting in their nutritional requirements. Earthworms are less common and of smaller average size than in moist calcareous mull, and although neither F nor H layers are clearly developed, litter tends to accumulate in larger amounts, especially under *Rubus*.

Except on sheltered sloping and valley sites with chalk at moderate depths (e.g. profile Bu 11, Table 1) brown earths under old-established beechwoods are strongly acid (pH H_2O 4·5–5·0) and the maintenance of mull humus is associated with an active organic cycle, as evidenced by accumulation at the surface of exchangeable calcium. In dense shade and on exposed slopes where the ground vegetation is scanty, earthworm

activity is less evident, and a tendency to mor formation is generally apparent, even where the subsoil is rich in calcium. On thick base-deficient plateau drift, well-developed mull soils are of limited extent and the majority of the beechwoods, conforming to Watt's (1934) sere B and to Brown's (1953) *Rubus-Oxalis* type, are characterized by humus forms of transitional character with local development of F and H layers, and thin, dark-coloured, weakly aggregated A_h horizons having a clear lower boundary.

Podzolic soils and podzols

Well-developed podzols are rare on the Chilterns proper, but 'podzolic' profiles with very acid mor humus, accompanied by discontinuous superficial bleaching of the mineral soil, are comparatively common. Described as 'degraded brown forest soils' by Brown (1953), soils of this type are invariably encountered in beechwoods and beech-oak woods of Watt's (1934) sere C (*Fagetum ericetosum*), characterized by a scanty ground vegetation of acidophile grasses (e.g. *Deschampsia flexuosa*) and mosses. Where developed as a phase of the Batcombe series on plateau sites, a superficial micro-podzol (Lyford, 1952) normally appears beneath the humus layer, and the yellowish sub-surface horizon, often with a feebly laminated structure, is appreciably more compact than in the corresponding mull soils. The following profile is representative.

L ($\frac{1}{2}$–1 in. thick).

F ($\frac{1}{2}$–1 in. thick) Dark brown matted decaying leaves threaded by fungal mycelium.

H ($\frac{1}{2}$–1 in. thick) Black humus, laminated in places and feebly aggregated into very fine crumbs; abundant fungal mycelium and small roots.

Micro-podzol

(Up to 1 in. thick) Thin dark grey laminated humose silt loam (A_h) overlying grey relatively humus-free silt loam (A_e), separated by a sharp boundary from a sinuous and discontinuous dark reddish-grey to reddish-brown seam (B_{Fe}) which is compact and weakly cemented.

A_1 (12–14 in. thick) Yellowish-brown, weakly laminated silt loam containing a few small flints and pebbles; faint paler-coloured mottling, with a few small Fe—Mn concretions below 6 in.; compact in place but friable when dug out; soft and light yellowish-brown to light yellow when dry; humus confined to occasional channels. Merging boundary.

B_t/g (18–24 in. thick) Strong brown to reddish-yellow, firm, slightly flinty, silty clay, increasingly mottled with very pale brown to yellowish-red; moderately well developed sub-angular blocky to blocky structure, with light brown, shiny aggregate faces. Ill-defined boundary.

On similar material, prominently mottled with light grey to red, the grey colours mainly associated with plastic clay coatings on structural faces and stones.

Lying with a sharp boundary on the mineral soil, and having a high C/N ratio (20–40), the humus layers almost certainly correspond to those originally described in beechwoods by Müller as *mor* or *torf* (Bornebusch, 1950). Earthworms and burrowing mammals are scarce or absent, and biological activity is largely confined to the H layer, the fine

coprogenic elements of which are attributed to small arthropods. The surface is firm under foot and after drying out in summer the mor absorbs succeeding rainfall like a sponge, so that the compact soil below may often appear quite dry after a lengthy spell of wet weather. The micro-podzol horizons show little tendency to thicken into normal podzols and their morphology, undoubtedly conditioned by the dense and silty nature of the soil, suggests comparison with moorland peaty gleyed podzols (Crompton, 1956) rather than with 'brown podzolic soils' representing an early stage of podzolization on well-drained coarse-textured materials. The incipient B_{Fe} horizon appears as a thin pan-like seam rather than as a diffuse ochreous zone, and in slight depressions where both litter and moisture tend to accumulate, the slightly thickened A_e horizons have a bluish cast, suggesting that the expression 'gley-podzolic' might be more appropriate.

On soils of the Charity and Winchester series, mor formation is mainly confined to exposed brows where the surface horizons are extremely flinty and the ground virtually bare of vegetation (e.g. profile Bu 56, Table 1). On these sites, the loamy A_1 horizons themselves appear strongly depleted of clay and iron oxides, and micro-podzols are less clearly developed, but superficial bleached flecks, bordered by minute iron-enriched seams, can generally be discerned beneath the black coprogenic H layer.

Well-developed podzols, grouped for survey purposes with the Berkhamsted series, are occasionally encountered on similar 'stony edge' sites where the plateau drift contains appreciable amounts of sand. The following description refers to profile Bu 80 (Table 1).

L	Thin and discontinuous (windswept site).
	Thin and discontinuous.
H	(½–1 in. thick) Very dark brown, loose, crumbly humus containing a few bleached sand grains; abundant fungal mycelium and fine roots.
A_h	(0–½ in. thick) Very dark grey, humose, structureless fine sandy loam, discontinuous. Clear boundary.
A_e	(6–7 in. thick) Pinkish grey, extremely stony, structureless, loose, fine sandy loam, locally humus-stained; stones, including flint pebbles and broken flints, bleached. Clear boundary.
B_h	(0–3 in. thick) Dark reddish-brown, extremely stony, structureless fine sandy loam, more compact than above and weakly cemented towards lower boundary; this horizon discontinuous. Merging boundary.
B_{Fe}/A_1	(8–11 in. thick) Reddish-yellow, extremely stony loam, darker in colour towards upper limits and paler below; friable when moist but appreciably more plastic than above; ochreous stains on stones, particularly in upper part, contrasting with bleached stones in A_e; weakly developed crumb to fine sub-angular blocky structure. Merging boundary.
B_t/g	(*c.* 12 in. thick) Strong brown to yellowish-red, very firm, very stony clay with sandy pockets, faintly to distinctly mottled with pale brown to red; structure ill-defined because of stones, but shiny clay-coated cleavage faces are common; few roots; ill-defined lower boundary.
	On similar material, consisting of numerous large flints in a mottled, more or less sandy, clay matrix with pockets of small flint pebbles.

Judging by comparative morphology and geographic relationships,

TABLE I

Profile no. and grid ref.	*Genetic soil type*	*Soil series*	*Horizon*	*Depth (in.)*	pH H_2O	pH M/100 $CaCl_2$	*Clay* %	*Organic carbon* %	*Nitrogen* %	C/N *ratio*	$CaCO_3$ %	*Exch.* Ca *(m.e./100 g.)*
Bu 20 830042	Rendzina	Icknield	A	0–4	7·9	7·6	11•	8·1	0·71	11	65	n.d.
Bu 101 833044	Brown calcimorphic	Coombe	A	0–6	7·8	7·5	24•	6·2	0·42	15	17	n.d.
			(B)	6–11	8·0	7·6	23•	n.d.	n.d.	n.d.	23	n.d.
			C	12–18	8·2	7·7	11•	n.d.	n.d.	n.d.	60	n.d.
Bu 78 839033	Brown calcimorphic	Coombe	A	0–3	7·7	7·0	36•	9·1	0·72	13	5·6	n.d.
			(B)	5–10	7·6	7·3	20•	n.d.	n.d.	n.d.	16	n.d.
Bu 17 827027	Brown calcimorphic	Wallop (Chalk at 11 in.)	A	0–5	5·6	5·1	48	5·1	0·41	13	0·3	36
			(B)	5–11	6·6	6·6	77	n.d.	n.d.	n.d.	nil	15
Bu 11 970158	Brown earth	Charity	A_h	0–4	5·6	5·2	28	5·6	0·43	13	nil	17
			A_1	4–11	5·4	4·9	30	n.d.	n.d.	n.d.	nil	14
			B_t	11–22	6·7	6·3	37	n.d.	n.d.	n.d.	nil	22
			C	22–30	8·2	7·7	29	n.d.	n.d.	n.d.	38	n.d.
Bu 55 833040	Brown earth	Charity	A_h	0–3	4·6	3·8	16	5·3	0·35	15	nil	5·3
			A_1	3–11	4·5	3·8	13	1·6	n.d.	n.d.	nil	1·4
			A/B	11–17	5·0	4·2	21	n.d.	n.d.	n.d.	nil	3·8
			B_t	17–27	5·3	4·7	44	n.d.	n.d.	n.d.	nil	22
				27–33	6·0	5·4	46	n.d.	n.d.	n.d.	nil	25
			C	33–39	8·0	7·5	38•	n.d.	n.d.	n.d.	33	n.d.
Bu 14 832021	Brown earth	Batcombe	A_h	0–1½	4·4	3·9	14	4·5	0·38	12	nil	1·7
			A_1	1½–8	4·5	4·1	17	1·5	n.d.	n.d.	nil	0·3
			A/B	8–16	4·5	4·1	29	n.d.	n.d.	n.d.	nil	0·1
			B_t	16–29	4·7	4·1	54	n.d.	n.d.	n.d.	nil	1·5
				36–60	5·0	4·0	58	n.d.	n.d.	n.d.	nil	5·2
Bu 16 828027	Brown earth	Winchester (Chalk at 15 in.)	A_h	0–2½	4·7	4·4	20	5·9	0·42	14	nil	6·4
			A_1	2½–7	5·3	4·9	25	n.d.	n.d.	n.d.	nil	2·3
			B_t	7–15	5·3	4·8	86	n.d.	n.d.	n.d.	nil	30
Bu 54 829027	Brown earth	Winchester (Chalk at 43 in.)	A_h	0–2½	4·8	4·4	16	6·0	0·45	13	nil	7·2
			A_1	2½–7	4·5	4·0	15	2·9	n.d.	n.d.	nil	2·7
			B_t	12–26	4·6	4·2	64	n.d.	n.d.	n.d.	nil	19
				26–37	5·0	4·5	87	n.d.	n.d.	n.d.	nil	28
				37–43	6·4	6·1	92	n.d.	n.d.	n.d.	nil	45
Bu 13 866014	Podzolic	Batcombe	H	½–0	4·1	3·5	n.d.	38	0·77	39	nil	n.d.
			A_1	1–6	4·2	3·7	17	1·8	n.d.	n.d.	nil	0·5
				6–13	4·4	4·1	21	n.d.	n.d.	n.d.	nil	0·7
			A/B	13–24	4·3	3·9	38	n.d.	n.d.	n.d.	nil	0·5
			B_t	24–36	4·2	4·0	67	n.d.	n.d.	n.d.	nil	1·2
Bu 56 830040	Podzolic	Charity (Chalk at 41 in.)	H	1–0	4·5	3·6	n.d.	31	1·5	21	nil	14
			A_e	4–10	4·7	4·0	15	n.d.	n.d.	n.d.	nil	0·7
			B_t	17–24	5·0	4·4	44	n.d.	n.d.	n.d.	nil	12
				24–32	5·4	4·8	43	n.d.	n.d.	n.d.	nil	18
				35–40	5·5	5·2	54	n.d.	n.d.	n.d.	nil	28
Bu 80 885006	Podzol	Berkhamsted	H	1–0	4·0	3·2	n.d.	35	1·70	20	nil	4·5
			A_e	1–6	4·4	3·6	7	3·1	n.d.	n.d.	nil	0·2
			B_{Fe}	8–16	4·4	3·9	14	0·98	n.d.	n.d.	nil	0·4
			B_t	18–30	4·3	3·9	56	n.d.	n.d.	n.d.	nil	0·1

• Determined after removal of carbonates.

this profile may be interpreted as a secondary humus-iron podzol superimposed on a strongly leached brown soil (cf. Lyford, 1952). Although the lower horizons are variable in thickness and degree of expression, the bleached sub-surface horizon (A_e), followed by horizons enriched successively in humus and iron,* is clearly eluvial, and there remains in places beneath the B_{Fe} horizon a second relatively pale-coloured clay deficient layer which seems to be a relic of a former A_1 horizon.

Discussion

The sequence of soil types under consideration is closely paralleled by developmental sequences established elsewhere on uniform calcareous materials where the geographic distribution of the types represented may be ascribed to the influence of relief and biotic factors in modifying profile development during Holocene times. In the loess region of Belgium, for example, where the typical soil on 'normal' sites under oak-hornbeam woodland is of brown-earth (*sol brun lessivé*) type, underdeveloped calcimorphic soils (*sol brun calcaire*, *pararendzina*) are associated with steep slopes or accelerated erosion, while the occurrence of more leached stages (*sol podzolique*; *sol podzolique à gley secondaire*) has been related to human intervention, particularly through the artificial establishment of beech high-forest during the last two centuries (Dudal, 1953). In the Chilterns, by contrast, characteristics acquired through the recent operation of soil-forming processes have been superimposed on a geographic association of parent materials ranging from pure chalk to non-calcareous superficial deposits which incorporate the more or less disturbed remains of pre-Holocene soil formations.

It has been argued by Duchaufour (1950) that on Jurassic limestones in Lorraine, where the natural climax is beechwood, the evolution of the soil from rendzina to brown forest soil is directly associated with the vegetational succession from basic grassland to beech forest. On the Chalk of the Chilterns, there is little evidence that soil evolution *in situ* has passed beyond the rendzina stage in Holocene times, since the brown calcimorphic soils are apparently confined to transported materials. That this is the case may be attributed to the general limitation of chalk outcrops to steep slopes or to the relative immaturity of the beechwoods examined, but from observations over a wider field it would seem that the development of acidity in thin soils overlying chalk is prevalent under old grassland as well as under woodland and is primarily related to the occurrence of drift impurities.

On calcareous drifts, including loess and Coombe deposits, it is reasonable to suppose that brown calcimorphic and brown forest soils represent successive stages of leaching, but the distribution of these types in the Chiltern valleys is undoubtedly affected by initial variations in chalk content as well as by the incidence of erosion and by the relative age and stability of the land surfaces concerned. As in the Belgian loess region, the normal effect of slope in retarding profile development is

* Confirmed by chemical analysis of clay fractions.

* Determined after removal of carbonates.

accentuated under cultivation, so that soils under old established beechwoods on valley sides tend to be more strongly leached than those on adjacent agricultural land which have been 'regraded' by accelerated erosion or by addition of chalky rain-wash.

The brown earth-podzol sequence is evidently conditioned in part by factors other than parent material, for although well-developed podzols are confined to appreciably sandy drift, profiles of both mull and mor types may be found on plateau sites with equally base-deficient subsoils.

It has been repeatedly observed that soils on exposed slopes where the ground vegetation is scanty are either more strongly leached or show a greater tendency to mor formation than otherwise similar soils on more sheltered sites, where mull with bramble or herbs is commonly found. That factors other than base-status are involved is shown by the occurrence of podzolic soils on flinty slopes within root range of chalk, where the litter is comparatively rich in calcium. On the site of profile Bu 56 (Table 1), for example, fresh beech leaves contained 1·3 per cent. calcium on a dry-matter basis, as against 0·59 per cent. on a plateau site with thin acid mull (Bu 14) and 2·7 per cent. on a rendzina (Bu 20). As noted by Brown (1953), aspect and exposure may be expected to affect biological activity on the forest floor both directly, through their influence on soil temperature and moisture conditions, and indirectly, by modifying the subordinate vegetation and hence the overall character of the plant debris. In the Ardennes (Pecrot and Avril, 1954) and in the Vosges (Duchaufour, 1955), an increased tendency to podzolization has been noted on south-facing slopes and attributed to depression of biological activity through lack of moisture at the time when temperature conditions are most favourable. In the Chiltern beechwoods, the constant occurrence of mor on the bare and windswept western margins of plateau woods on level sites suggests that exposure to prevailing winds is a more significant factor than aspect as such in modifying the course of litter decomposition.

It has already been noted that Dudal (1953) attributed the 'degradation' of loess-derived *sols bruns lessivés* to the establishment of beech high-forest, its effect being most marked on level sites. Watt (1934) adduced evidence that the beech, by virtue of its resistant litter and its effect on soil climate, fosters mor formation on base-deficient soils in the Atlantic region to a greater extent than either oak or ash, and suggested that it might thereby render soil conditions unsuitable for its own regeneration. More recently, Dimbleby and Gill (1955) have shown that establishment of beech in New Forest oakwoods with sandy soil is associated with advanced podzolization which cannot be attributed either to the oak or to a former heather cover.

According to Duchaufour (1956), the degradation of climax brown forest soils under the influence of induced changes in vegetation proceeds in a manner determined by the nature of the parent rock. On coarse-textured siliceous sediments, the ultimate stage of degradation is represented by a humus-iron podzol under dry *Calluna* heath, but where the substrate is clayey or otherwise impervious, the evolutionary tendency is rather towards increasingly hydromorphic *pseudogley* or

gley-podzolic profiles and may be associated with the replacement of forest by wet-heath vegetation.

Although a tendency to mor formation under dense beech canopy is widely apparent on the Chiltern plateau, there is no conclusive evidence that beech high-forest has exerted an over-riding influence on soil development. It may be that certain of the plateau woods with good mull soil were planted on agricultural land which had received dressings of chalk and that the beech has not been in occupation long enough to make its presence felt, but the frequent occurrence of mull and mor in different parts of the same wood suggests that the rate and extent of mor formation is governed by environmental factors.

The occurrence of micro-podzols on Batcombe silt loam is generally associated with pronounced subsoil mottling, and Brown (1953) has suggested that inherently imperfect drainage, by restricting root development with consequent liability to seasonal drought, may limit the turnover of nutrients and check biological activity to the extent that mor formation is materially favoured. At the same time, the possibility exists (Manil, 1956) that beech high-forest may itself contribute to poor aeration in these base-deficient soils, its shallow-rooting habit leading to deterioration of subsoil structure, and its acidifying tendency to increased clay deflocculation. However, neither micro-podzol nor *pseudogley* effects are confined to beechwoods; both are found under old oak stands, and well-developed gley-podzolic soils with strongly compacted, mottled B horizons are common in certain Hertfordshire oak-hornbeam woods on acidic material. Nor can it be said that plateau beechwoods with mull soil are invariably of more recent origin than those in which mor has developed on similar substrates. A more probable explanation of observed differences, in so far as they are not conditioned by site characteristics, may lie in recent woodland management. A tendency to mor formation is often associated in mature plateau woods with dense stands of undersized, slow-grown trees, under which both ground vegetation and natural regeneration have been largely suppressed. According to Brown (1953), these conditions result from uneven application of the selection system whereby, following the declining demand for small timber, the woods were inadequately thinned and only the larger, better-quality trees cut out. Where gaps have arisen in such woods, increased biological activity and breakdown of the mor humus has been observed, accompanied on sheltered sites by the appearance of *Rubus* and nitratophilous herbs.

The foregoing observations suggest that mor formation under beech is to some extent a cyclic phenomenon, readily influenced by environmental factors and by management practices, and that only where site characteristics are particularly favourable (e.g. on base-deficient sands) does it result in advanced podzolization. This conclusion is afforded some confirmation by Romell's (1954) observation that while mor was widespread in Denmark in P. E. Müller's time, 'now it is rare; the old beech stands are now gone, and in the young forests, mull exists in its stead'. In Romell's view, mor formation results from intensified competition for nitrogen by roots and mycelia as the stand

ages. Death of trees from natural causes or by felling is followed by release of available nitrogen, a dense ground flora develops, and mor disappears.

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THE GEOCHEMISTRY OF BASALTIC MATERIALS AND ASSOCIATED SOILS OF SOUTH-EASTERN SOUTH AUSTRALIA

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Summary

Four profiles in the Mt. Burr forest area of south-eastern South Australia have been examined in detail. Two profiles were podzolized deep aeolian sands overlying buried soils which had developed on basaltic tuff, a third profile was developed on olivine basalt while the fourth was a composite profile developed on basaltic tuff and containing a buried profile formed on an earlier ash shower.

The main factors operative in influencing the geochemical distribution of the elements in these profiles were the translocation of elements by plant growth and their relative mobility on weathering, association with the clay fraction, and restricted drainage. In the aeolian sands Ca, Mn, and V with lesser amounts of K, P, Mo, Cu, Mg, Zr, and Al, were the elements which generally accumulated in the surface horizon as the result of plant action. In the surface soils of volcanic origin Ca, Mn, P, and Mg with lesser amounts of Cu and K accumulated. The highest concentrations in the clay fraction were, in general, for the aeolian sands Al, Fe, Ga, V, and Ni, and in the basaltic soils Na, Al, Ga with, to a lesser extent, K, V, P, and Ni. In the soils developed on basaltic material the elements most readily lost from the weathering zones during soil formation were in decreasing order of magnitude, Ca, P > Na, Mg, Co, Zn > Cu, Mn > Ni. K, V, Ga, Mo, Fe, Al, Ti, and Zr were in general much less mobile and tended to remain incorporated in the weathering products and concentrated in the upper weathering zones. P, Zn, and Cu and to a lesser extent Mn, Fe, Ni, Co, and Ca were found to be more readily lost on weathering under conditions of restricted drainage.

The elements most concentrated in the hardpan of a ground-water podzol were, in decreasing order of magnitude, Fe > Al $\gg$ V, Zn, Ni > P, K, Mo > Na, Mn, Cu, and Ti. When the more strongly cemented nodules were separated for analysis it was found that relative to the matrix Fe > Al, V, and P, in that order, were most concentrated. Zn alone was lower in the nodules than the sandy matrix. Mn and Mo were most concentrated in the upper part of the hardpan, and Zn, V, Ni, Cu, Ti, and P in the lower part.

Some of the mineralogical changes which have taken place during the weathering of the basaltic material have been studied by examination of sand and clay fractions of the soil and thin rock sections. In the olivine basalt, the plagioclase and, to a lesser extent, olivine have weathered most readily. The main weathering products of the soil developed on the olivine basalt were kaolin and haematite. In the tuff the first important weathering product was montmorillonite, formed by the breakdown of the volcanic glass. This montmorillonite was found to break down in the upper weathering zones of the soils formed on tuff to give kaolin and goethite.

I. *Introduction*

THE geochemical study of soil profiles in relation to their development has not been undertaken on a very large scale. Many such studies, although adding to the general understanding of the subject, are unfortunately of limited value because few elements have been studied and valid interpretations of the results are not always possible. In many soils numerous pedological processes may operate concurrently and the

complications due to the variations in parent material considerably reduce the value of detailed studies.

There are numerous references in the literature to the distribution of trace elements in soils. Many analyses have been carried out as routine surveys (often using surface soils only) in order to gain knowledge of any present or future nutritional disorders arising from the deficiency or excess of particular elements. Analysis of vegetation associated with the soils under survey has often been carried out to help assess the availability of the elements concerned. Only in a few cases has any attempt been made to interpret the results gained in terms of pedological processes. An excellent bibliography concerning the occurrence of trace elements in soils has been published by Swaine (1955). In the literature, the most commonly discussed factors affecting distribution of trace elements in the profile are those of surface enrichment by plants, the effect of waterlogged conditions, the varying clay content of the profile and overall leaching (Mitchell, 1955).

In the project discussed here the geochemistry of four deep soil profiles developed on basaltic tuff and basalt, two of which are overlain by aeolian sands, was studied in detail. The profiles were sampled in the Mt. Burr forest area of south-eastern South Australia. The Mt. Burr range, which consists largely of volcanic hills of tuff formed during late Pliocene and Pleistocene times, has since been modified by marine erosion during the Pleistocene and more recently still has been covered by a mantle of aeolian sand. Apart from the tops of the hills there is very little basaltic material without this mantle of sand. These podzolized sands are now largely used for plantations of *Pinus radiata*. The distribution of 18 elements in parent materials, soil profiles, and clay fractions separated from selected horizons has been determined in order to study their reorganization under the influence of the various processes of weathering and soil formation, with particular reference to the basaltic materials. The opportunity was also taken to study the influence of these buried soils on pine growth and other pine-soil relationships as it had been suggested by Stephens *et al.* (1941) that the presence of accessible weathering volcanic material beneath the aeolian sands was important in the nutrition of the pine trees.

II. *Methods*

Excepting soil profile A185, which was sampled from a quarry face, all profiles were taken from a pit face for the top 3 ft. and below this by soil auger. Mechanical analyses, chlorides and nitrogen determinations were carried out by the methods given by Piper (1942). Sand fractions were retained for mineralogical examination. The clay fractions were separated by decantation (Piper 1942), using nothing stronger than 0·02 N ammonia as the dispersing agent.

Co, Ni, Zr, Cu, V, Mo, Ga, and Mn were determined quantitatively by the standard emission spectrographic methods developed in these laboratories. All samples were volatilized in triplicate in a 15-ampere d.c. arc, using anode excitation. Standards were prepared by the method of successive additions. Fe, Ti, and Zn were determined by

TABLE I

Analyses and Per cent. Variation in Parent Materials

	Per cent.									*p.p.m.*									
Rock no.	Si	Al	Ti	Fe	P	Na	K	Ca	Mg	Co	Zr	Ni	Cu	V	Mo	Ga	Mn	Zn	*Description*
185/9	21·0	6·46	1·4	7·27	0·44	2·79	0·64	8·00	6·70	59	510	480	150	570	6·5	32	1550	91	Olivine basalt Mt. McIntyre
R165	20·4	6·19	1·4	7·06	0·44	2·99	0·80	7·79	7·90	56	510	390	110	580	8·9	31	1400	..	Olivine basalt Mt. Graham
Average	20·7	6·33	1·4	7·17	0·44	2·89	0·72	7·90	7·30	58	510	440	130	580	7·7	32	1500	91	Basalt
% variation	3	4	0	3	0	7	20	3	15	6	0	20	30	2	30	3	13	..	
A699	—	—	—	—	—	—	—	—	—	52	320	640	170	350	5·8	20	1150	..	Greenish Tuff Mt. Muirhead
P28	—	—	1·4	7·20	—	—	—	—	—	45	390	480	120	340	4·4	21	1100	..	Grey Tuff Mt. Muirhead
RO	19·5	5·29	1·4	7·83	0·34	1·02	1·71	7·29	10·1	57	300	710	120	290	4·0	22	1100	93	Compact Tuff Mt. Muirhead
RP42	24·1	5·45	1·4	7·62	0·33	0·59	0·94	7·79	5·31	50	400	390	130	300	5·8	25	1150	105	Tuff Campbell's Hill
Average	21·8	5·37	1·4	7·73	0·34	0·81	1·33	7·54	7·7	51	350	560	130	320	5·0	22	1100	99	Tuff
% variation	20	3	0	3	3	50	60	7	60	25	30	60	30	20	30	20	0	12	

No data —

$$\% \text{ variation} = \frac{\text{Range}}{\text{Mean}} \times 100$$

X-ray fluorescent spectrographic methods. Si and Al were determined colorimetrically after fusion with sodium carbonate and P, Na, K, Ca, and Mg after digestion of the soil with hydrofluoric and sulphuric acids. P was estimated colorimetrically, Ca and Mg by titration with E.D.T.A. solution, and Na and K by flame photometry.

All analyses of soils, rocks, and clays are reported on the basis of ignition at 600° C.

III. *The Nature of the Basaltic Parent Material*

Fresh parent rock could be sampled only from the profile on weathering olivine basalt on Mt. McIntyre. In the other three profiles the lower horizons had the appearance of weathering tuff, the harder pieces of basalt contained therein being often recognizable. As it was of importance in this study to know the composition of the parent material and its homogeneity several samples of tuff varying in appearance and texture were collected from Mt. Muirhead and Campbell's Hill. Basalt was collected from Mt. Graham for comparison with that on Mt. McIntyre. On the basis of the analyses for trace elements in the tuff samples, the two most divergent samples were chosen for chemical analyses. The amount of variation between samples for each constituent was measured by the ratio of range/mean expressed as a percentage, the range being the difference between maximum and minimum values (Table 1). It may be seen that for the tuff Ni, Na, K, and Mg are the most variable, Mn, Zn, Al, Ti, Fe, Ca, the most consistent; the remaining elements vary to an intermediate extent. For the basalt Ni, Cu, Mo, K, and Mg show greatest variation with the remaining elements comparatively constant in the two samples analysed. On the basis of these values it is considered that the average composition of the tuff samples analysed should give the order of the composition of the tuff parent material beneath the three profiles sampled. This average composition was used to give some estimate of the further variation to the parent material. The only significant differences between the mean values for the major elements in the basalt and tuff were for Na, which was over three times as great in the basalt, and K which was twice as great in the tuff. The variation of Na between basalt and tuff is no doubt a reflection of the ease with which this element is lost on weathering; the glass of the tuff would of course be much more prone to weathering than the primary minerals of the basalt. As far as the trace elements were concerned Ni was the only one that occurred to a lesser extent in the basalt than in the tuff; Co, Zn, and Cu were about the same in both, while Ga and Mn were a little higher and Zr, V, and Mo were much higher in the basalt.

The similarity in the chemical composition of the basalt and tuff is good evidence that the tuff contains very little country rock. Thin sections showed that the tuff consisted mainly of altered basaltic glass, some basalt lapilli, crystals of olivine, small laths of augite with lesser amounts of quartz, calcite (possibly from the country rock, Miocene limestone), and magnetite. Under the petrological microscope this altered glass resembled material known as pelagonite but X-ray diffraction analyses indicated that this was largely montmorillonite. The only

regular trends in the composition of the tuff were in the variations found for Mg, Ni, and Zr. The samples with the highest Mg and Ni have the lowest Zr and vice versa. The geochemical association of Mg and Ni is well shown by the constancy of the Mg/Ni ratio even though the elements vary twofold in the two samples examined. This variation is no doubt a reflection of the original olivine and augite in the ejected material as these minerals would be the main source of the Mg in the rock. Zr replaces the common ions in minerals only with difficulty because of its large ionic radius and charge. It is also known that it is usually at too low a concentration to crystallize as zircon in the basaltic magma. Zr, then, may be highest in the tuff which originally contained the greatest amount of glass.

A sample of olivine from Mt. Gambier was analysed and although this is not necessarily the same as that in Mt. Burr area, it gave the order of the concentrations to be expected. This olivine had 1,400 p.p.m. of Ni and only 34 p.p.m. of Zr.

IV. *Distribution of Elements in the Profile*

In this paper the distribution of some of the elements in the four profiles studied is shown by diagrams rather than extensive tables. The detailed chemical and mechanical analyses and morphological descriptions of the profiles are presented and discussed in an internal report* of the Division of Soils, C.S.I.R.O., Australia.

1. *Profile A180—a ground-water podzol on aeolian sand overlying a soil developed on basaltic tuff*

The profile is that of a ground-water podzol, mapped as Young sand (Stephens *et al.*, 1941) overlying weathered basaltic tuff. The profile was sampled in a very poor stand of *Pinus radiata*. The surface grey sand merges into almost white sand in turn overlying the dense dark brown organic hardpan which extends from 4 ft. to 6 ft. This hardpan has formed in the region of the surface of the fluctuating water-table. The lower illuvial horizons consist of a shallow yellow sand overlying gleyed horizons which increase in clay content with depth from 10 to 40 per cent. at 9 ft. The buried soil developed on basaltic tuff extends below 9 ft. and consists of stiff, plastic gleyed clays in the original surface horizons but becomes friable in the lower, less weathered zones. In the upper profile coarse sand/fine sand ratios are fairly constant, except in the surface, and suggest that the aeolian parent material was reasonably homogeneous. The sand fractions of the aeolian sand consisted almost entirely of quartz, with odd grains of apatite, zircon, and feldspar. The sand fractions of the buried volcanic profile contained quartz, weathered rock fragments, and occasional very weathered augite laths. Mixing of the different materials during deposition of the sand was restricted to the bottom sample of the aeolian profile.

Although most elements studied were concentrated in the surface horizon the effect was most apparent for Ca, Mg, and Mn. Al, Fe, P, Na, K, and Mo decreased with depth to the A_2 horizon. The contrasting

* Divisional Report No. 3/57. Copies of this may be obtained on request.

increase with depth to this horizon of the least mobile elements, Zr and Ti, may indicate a higher degree of weathering in this horizon. On the other hand the decrease with depth for some elements may be a reflection of the organic matter content as this is also lowest in the A_2 horizon.

All elements except Co (which was not detected in any part of the profile), Ca, and Zr were concentrated in the hardpan taken as a whole.

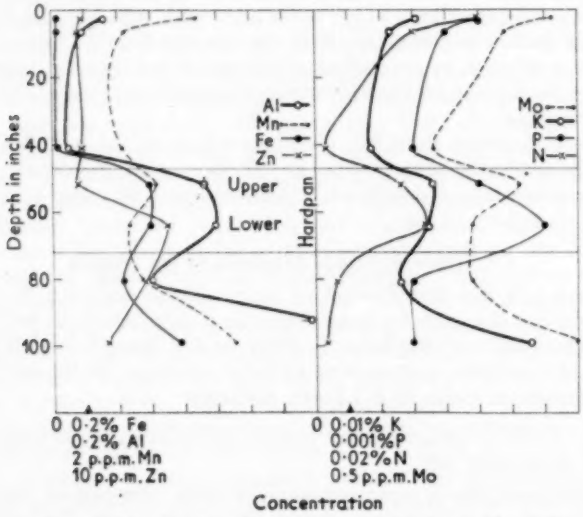

FIG. 1. Distribution of some elements in the hardpan of profile A180.

Using the A_2 horizon as a basis the order of concentration for the whole hardpan was Fe > Al ⩾ V, Zn, Ni > P, K, Mo > Na, Mn, Cu, and Ti. Ni was measurable for the first time and Ga was just detected as in the surface horizon. Some elements showed a differential distribution between the lower and upper parts of the hardpan. Mn and Mo were more associated with the upper part while Zn, in particular, and also V, Ni, Cu, Ti, and P were more concentrated in the lower part. In the upper hardpan the more firmly cemented parts were separated for analysis and compared with the brown sandy matrix which comprised three-quarters of the whole horizon by weight. The elements concentrated in the nodules were, in decreasing order of magnitude, Fe > Al, V, P ⩾ Na, K, Ni > Mn, Mo. Zn alone was less in the nodules than the sandy matrix. The concentration of Al, Fe, V, and P in these nodules suggests that V and P may be fixed here by the formation of iron and aluminium vanadates and phosphates, possibly as adsorption compounds.

The differential distribution in the various parts of the hardpan (Fig. 1) may have been influenced by several factors. In the case of Mn it may well be that the mobile manganous ions, produced in the lower

horizons under the influence of waterlogging, are once again fixed as higher oxides in the upper region of the fluctuating surface of the water-table. However the group of elements, Zn, Cu, Ni, P, and V are all more concentrated in the lower part of the hardpan even though they are also mobilized by waterlogged conditions. The influence of these conditions is discussed later.

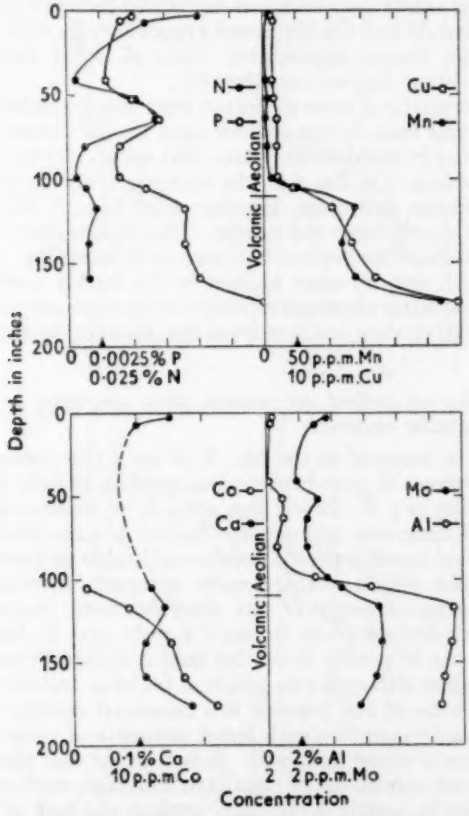

FIG. 2. Distribution of some elements in profile A180.

The amount of organic matter, although increasing with depth in the hardpan, did not appear to control the distribution of all the elements. Movement of material from the surface, in association with the organic matter formed from decomposing pine litter, may have influenced the composition of the upper part of the hardpan in the 40–50 years since the establishment of a pine forest and changed the equilibrium established under the previously existing heath-type vegetation.

A third factor may have been the movement of elements with Al and

Fe in the processes of podzolization. In summary, the present distribution of elements is probably due mainly to the differing mobilities under the influence of podzolization together with the more recent preferential leaching of some constituents from the upper hardpan and, more recently still, additions of Mn and Mo organic complexes from the decomposing pine litter.

In the gleyed sandy clay horizons below the hardpan the clay content rose steadily and Al and Ga increased proportionally with it. P, Cu, Ca, and Zn did not change appreciably while all other elements studied increased to a lesser degree than the clay.

The concentrations of most elements were much greater in the surface of the buried soil than in the aeolian sand profile above (Fig. 2). The small peak in the N distribution curve also shows clearly the position of the old land surface. Ca, Zn, and Mn were relatively concentrated in this old surface horizon, and these, together with Mg, P, Ni, Co, and Cu, increased with depth down the profile. These elements were apparently readily leached from the surface horizons on weathering. By contrast V, Mo, Ga, Zr, Al, and Ti were highest in the highly weathered surface horizons. These latter elements tended to be incorporated in the weathering products rather than leached from the weathering zone.

2. Profile A184—a podzol on aeolian sand overlying a buried profile developed on basaltic material

This profile is mapped as the Mt. Burr sand (Stephens *et al.*, 1941). It has an A_1 horizon of grey-brown sand grading to light brownish sand in the A_2 horizon at 5 ft. Below this are 2 ft. of nodular brownish-grey sand, a zone of some clay and organic-matter accumulation. The upper part of the buried basaltic profile consists of friable yellowish to reddish-brown clay loam which overlies more compact, mottled horizons at depth. Mineralogical study of the sand fractions showed that some mixing of materials took place during the early ages of deposition of the aeolian sands. As in profile A180 the sand fractions of the aeolian part were mainly quartz although odd grains of feldspar and zircon were seen. The sand fractions of the basaltic soil consisted mainly of weathering pieces of tuff and magnetite with lesser amounts of quartz, augite, and apatite. No zircon could be found. It is thought that the instability of iron oxides under conditions of restricted drainage, such as occur in the basaltic material in profile A180, may explain the lack of magnetite in the sands of that profile.

Many elements were higher in the present surface horizon than underlying layers, but Ca, Mn, V, and Cu showed the greatest concentration there. Most elements decreased to a minimum in the A_2 horizon. As in profile A180 this trend may reflect the association of some of the elements with organic matter or the greater weathering and leaching that has occurred in this horizon. Although Co was present in pine needles collected as A_{00} litter it was not detected in the aeolian soil profile. Apparently this element is not strongly held in the organic matter of the surface horizons although it has been reported as a surface enrichment in

other countries. Ga was just detected in the surface horizon of both aeolian sand profiles but not again till the B horizons.

The following order of concentration in the nodular B horizon (in relation to the A_2 horizon) is similar to that found in profile A180: Fe > Al, Ti, K, V, Ni > P, Na, Ca, Mo > Mg, Mn, Cu. The increases

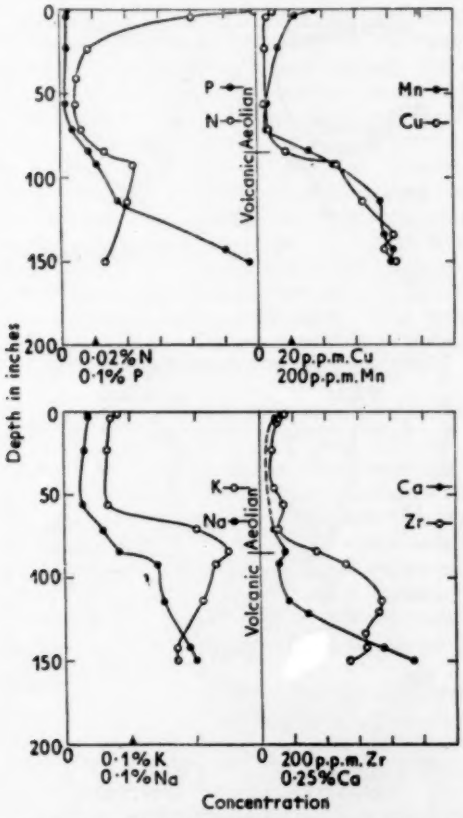

FIG. 3. Distribution of some elements in profile A184.

noted for some elements, such as Ni, V, K, and Mo, are too great to be accounted for by increase in clay content alone. In the B horizons of both profiles Ni and V are the elements most associated with Fe and Al. A marked increase in the concentration of all elements was noted in the lowest part of the B horizons due to the admixture of the basaltic material.

The surface horizon of the old basaltic soil, shown as such by a peak in the N distribution and a decreased pH, contains a considerable amount of quartz of aeolian origin, which, by its diluting effect, has masked the effect of surface concentration. In this profile P, Na, Ca, Mg, Cu, and

Mn all increase with depth (Fig. 3) and are therefore apparently lost from the surface by weathering processes. Al, Ni, Co, and Ga showed no marked change with depth because relatively unweathered material could not be reached by boring. V, Mo, Ti, Fe, Zr, K, and Zn decrease with depth and have apparently concentrated during the processes of weathering.

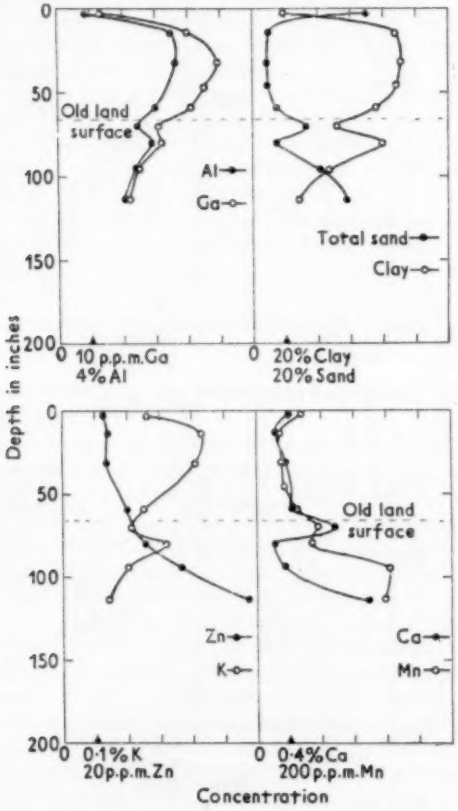

FIG. 4. Distribution of some elements and size fractions in profile A189.

3. *Profile A189—a double soil profile developed on basaltic tuff*

This soil is developing on weathering basaltic tuff and is not associated with either aeolian sand or pine forest. Although it is apparent in this area that there must have been a succession of ash showers the buried profile shows that, at least at one stage, the volcanic activity abated for a considerable period, sufficiently long for a soil to be formed. Pieces of carbon were noted near and up to 2 ft. below the interface of

the two profiles. The occurrence of a similar texture profile in both parts (Fig. 4) and the reddish colour of an old surface horizon are further evidence for the existence of a buried profile. The upper profile is more weathered than the lower one, the clay content of the horizons below the surface being 70–90 per cent.

As the surface of the field in which the profile was sampled had been cultivated at one stage it is possible that the original concentration of elements in the surface may have been affected. Mn and Ca are the only elements concentrated in the present land surface. All elements except Zr, Zn, and Na are much lower in this surface loam than the underlying horizons of higher clay content. In the upper profile Zn, Zr, Cu, Mn, Ca, Mg, Na, and Ti increased further with depth while Al, Ga, V, Mo, and K varied roughly with the clay content. Contrary to the trend found in other profiles the P content has decreased with depth in the upper profile. This may be explained by a higher amount of organically combined P as the organic matter content of this profile is much higher than of the others studied. P, Ca, Mg, Mn, and Cu are concentrated in the old land surface. There may also have been accumulation of Mg, Cu, and P at the present surface prior to cultivation. The general distribution of the elements is the same in the lower profile as the upper except that P increases and Zr is fairly constant with depth.

4. *Profile A185—a soil profile developed on olivine basalt*

This profile was sampled from a quarry face on the top of Mt. McIntyre. Below 8 ft. random pieces of decreasingly weathered rock were sampled to 17 ft. The present surface horizon was suspect because of farming and, later, quarrying operations near the site. The soil profile consists of reddish-brown to yellowish-brown sandy clays with clay content up to 25 per cent. The olivine basalt appeared fairly consistent in the field except that some parts were more vesicular than others.

The quartz content of this profile decreased with depth. In each horizon most of the quartz was in the coarse sand fraction and has probably come from the surface.

P, Mn, and Ca were the elements most concentrated in the surface horizons. The main feature in the distribution of the various elements is the horizon A185/3 which appears to be the zone of greatest weathering. Although this horizon occurred at some depth (30–48 in.) it was probably the sub-surface horizon of the original profile. In addition to the appearance of the present surface horizon in the field, the N profile (Fig. 5) also suggests that it was not formed *in situ*. The low content of P, Na, Ca, and Mg in this horizon (A185/3) suggests that they were readily leached from it during weathering. By contrast Zr, Al, Fe, and Ti are highest in this horizon and are apparently concentrated during weathering. Mg and Na increased with depth for the complete profile while P, Ca, Cu, and Mn, below the surface horizons, increased with depth in the 'soil' profile but did not vary appreciably in the 'rock' profile (Fig. 5). The remaining elements showed no significant trend with depth. Apatite, which would account for most of the P in the basalt, appears to have resisted weathering in the lower 10 ft. of the profile,

constituting the zone of weathering basalt, but in the soil above appears to have broken down rapidly under the different conditions of weathering which exist. Similarly the loss of Ca is markedly increased in the upper part of the profile, compared with the weathering rock profile.

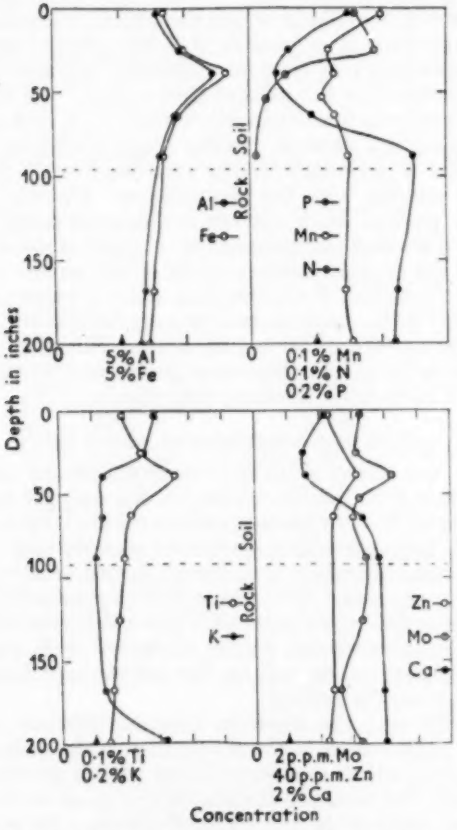

FIG. 5. Distribution of some elements in profile A185.

The different rates of weathering of Ca and P, in particular, in the two parts of the profile stress the difference between the profile of the soil and that of the weathering parent material.

V. *Mineralogy of Weathering in the Basaltic Material*

Thin sections were made of the basalt in various stages of weathering. The main minerals present were olivine, augite, and plagioclase, the latter being largely altered in the freshest sample examined. The augite was much more resistant to weathering than the olivine and indeed

occurred commonly in the sand fractions throughout the profile. Olivine also weathered readily giving a light brown unidentifiable isotropic material on the edges and sometimes along fractures of the crystals. Magnetite was formed as a product of this weathering and in the most weathered basalt sample examined most of the crystal shape of olivine was packed with magnetite.

The clay minerals in the soil on this basalt were kaolin and haematite. The kaolin mineral was probably halloysite but it could not always be positively identified. The kaolin has probably formed from the feldspar and the haematite from the magnetite as the latter mineral was not common in the soil. Although the basalt on top of Mt. McIntyre has a similar chemical composition to the basaltic tuff it had different weathering products. This could be due to the different drainage conditions or the different mineralogical composition of the basalt. In this well-drained site, 400 ft. higher than other sites sampled, the bases could be much more readily leached away so that kaolin minerals would be preferentially formed.

Thin sections of the tuff contained mainly volcanic glass, partially weathered to montmorillonite and lesser amounts of kaolin, olivine, and very altered basalt lapilli. This volcanic glass would constitute the main soil forming material of the tuff. It seems likely that the first important weathering product in the tuff profiles, regardless of drainage conditions, was montmorillonite as this mineral was found at depth in all profiles and in the relatively fresh rock itself. The common formation of montmorillonite from basic rocks under conditions of restricted drainage is well known. Hosking (1940) in some Australian soils found that basaltic rocks formed mainly kaolinitic minerals under conditions of free drainage and montmorillonite under impeded drainage. It may be then that restricted drainage conditions have also encouraged the formation of montmorillonite, particularly in the early stages when there would be sufficient bases present in the environment.

In soils developed on tuff, particularly in the upper horizons, the base status has decreased due to more intense weathering and leaching. Under these conditions the montmorillonite is apparently unstable and breaks down to kaolin and goethite. Mineralogical analyses of the clay fraction of the soils on tuff have shown, in general, that montmorillonite increases with depth and goethite decreases with depth.

VI. *General Discussion*

Mitchell (1955) has said that 'neither the rather scattered results in the literature nor the findings at the Macaulay Institute suggest any simple trend in the contents of the different trace elements in soil profiles that can be ascribed to pedological processes'.

Although this is also true in the profiles studied, the general effect of some of the factors has been recognized and evaluated. The many interacting processes operative in the soil profile, together with the uncertainty of homogeneity of parent material, have made detailed interpretation of many of the results impossible.

1. *Organic matter*

A prominent feature of each profile was the organic accumulation in the surface horizon even though the organic-matter content of the soils, as shown by N content, and the associated element accumulations were not as great as those often quoted in other countries. In profiles A180 and A184 this surface accumulation would have been largely influenced by the pine trees which have been established for 40–50 years. In profile A180, bracken growth has also contributed. The influence of the material translocated by the original native vegetation cannot be accurately assessed, but due to the cultivation prior to planting its residual effect in the present pine plantations would probably not be great. In three cases surface accumulations have been noted on the older volcanic soils, now buried beneath the present soil. In general, the same elements were found to accumulate in these as in the present surface horizons. On the aeolian sands the elements which generally accumulated were mainly Ca, Mn, and V with lesser amounts of K, P, Mo, Cu, Mg, Zr, and Al. In view of the work of Vlamus and Pearson (1950) it is possible that Zr may have been circulated by plants, but as it occurred mainly as zircon in the aeolian sand, it is more likely that the concentration of Zr in the surface was a relative effect due to the removal by leaching of the more soluble constituents. On the basaltic soils mainly Ca, Mn, P, and Mg, with lesser amounts of Cu and K, concentrated in the surface horizons.

Although the apparent surface accumulations in some circumstances may in part result from aeolian accessions, the similar effects noted in profiles of differing locality, parent material and age suggest that the results are due to plant accumulation.

It is well known that Ca, Mg, and K accumulate in the surface horizons by plant action, but some of the trace elements often found concentrated in the humus layers of soil in other countries had not accumulated here. Mitchell (1945) found Co and Ni concentrated in the organic litter of forest podzols. According to Mitchell (1955) the uncultivated soils of the Scottish moorlands, when calculated on a mineral basis, show this surface enrichment for Ag, Cu, Mo, Pb, Sn, and Zn. Pb in particular has also been noted as surface enrichment by Butler (1954), Wright *et al.* (1955) and Goldschmidt (1954). Although Pb was not determined quantitatively in this study, inspection of the spectrograms showed that it was present (approximately 20 p.p.m.) in the soils of basaltic origin but had not concentrated in the surface horizons.

2. *Clay*

By comparing the composition of the soil in selected horizons with that of the clay separated from it, it was found that in general certain elements were strongly associated with the clay fraction. In the podzolized aeolian sand most elements were higher in the separated clay fractions than in the total soil; in particular Al, Fe, Ga, V, and Ni were strongly, often completely, concentrated in the clay fraction of a horizon. In the basaltic soils Na, Al, Ga, in particular, and K, V, P, and Ni, to a lesser extent, were concentrated in the clay fraction relative to the whole soil. Although Co, Zn, Cu, Ga, and Ni have often been associated

with the clay content by many other workers on the geochemistry of trace elements in soil, only the latter two elements appeared to be so associated in these soils.

3. *Mobility on weathering*

An attempt was made to assess the reaction of the different elements to the processes of weathering. Some elements, on being freed from the weathering minerals, tended to remain and become incorporated in the weathering products while others were readily lost by leaching. These mobile elements, having been leached from the weathering zone, may be precipitated or absorbed lower in the profile, depending on the conditions prevailing there, or they may leave the whole system. On the basis of the change in the composition of the clay fraction with depth and assuming that weathering intensity increases towards the surface, the following general order of mobility is suggested for the elements in soils on basalt in this area: Ca, P > Na, Mg, Co, Zn > Cu, Mn > Ni > K, V, Ga, Mo, Fe, Al, Ti, Zr.

The increase of elements such as Co, Cu, Mg, and Zn with depth in the clay fraction was most apparent in the profiles A189 and A180 on basaltic tuff. This was probably due to the later breakdown of the initially formed montmorillonite, under the more severe weathering conditions existing in the upper horizons of the profile. X-ray diffraction analyses showed that the montmorillonite increased with depth. When montmorillonite is formed from the volcanic glass, it incorporates such elements as Co, Cu, Mg, Fe in its lattice. Even at this initial stage of clay formation a proportion of each of the mobile elements may be lost in solution. When the montmorillonite weathers to kaolin, certain of the elements previously in the montmorillonite structure may not be readily incorporated in the new structure because of the new spatial and charge requirements necessary. Co, Cu, and Zn, for example, have similar ionic radii to ferrous iron and Mg and may replace these latter ions in montmorillonite but on breakdown to kaolin they, together with Fe and Mg, will not be so readily incorporated in the new structure. The Fe tends to form goethite but much of the Co, Cu, and Mg is leached from the soil. By contrast, Ga decreases with depth in the clay fractions because of the ease with which it replaces Al in both minerals. The loss of major elements, such as Mg, on breakdown of montmorillonite in effect increases the proportion of Ga in the kaolin. Another factor contributing to this change with depth could be the accumulation, by adsorption, of the liberated ions by the clays of the lower horizons. The higher cation-exchange capacity of the montmorillonitic clays at depth would favour this accumulation. Study of the general distribution of the elements in the profiles also suggests that the elements Ca, Mg, P, Mn, Cu, and Na and to a lesser extent Co, Ni, and Zn, are readily lost from the upper horizons during weathering. Calculations of the gains or losses of several elements during weathering in the profile on basalt, using Ti as a weathering index (Tiller, 1957), allowed the same general conclusions on this matter.

Co and Zn are more stable to weathering processes in profile A185 on

olivine basalt. The volcanic glass of the tuff releases ions such as Co and Zn much more readily than the augite of the basalt. The higher resistance of augite to weathering in basalt may also explain the much higher Ca and Mg contents of the soil on it compared to the soil on tuff.

4. *Drainage*

The presence of a fluctuating water-table in some of the profiles studied has undoubtedly had a powerful influence on the rate and type of weathering processes taking place. The gleyed conditions are much more prominent in the Young sand profile because of its topographic position. The influence of restricted drainage has been studied in two ways. Firstly, two profiles A180 and A189 were examined. Both were developed on basaltic tuff of similar age, the former being gleyed and the latter fairly freely drained. Comparison of horizons in each profile that have been similarly weathered, as shown by clay content, suggested that the following elements were most readily mobilized under the influence of restricted drainage conditions in this basaltic material: Cu, P, Ca > Zn, Ni, Mn > Co. Secondly, the effect of restricted drainage has been assessed by the comparison of separated clays from adjacent horizons, one of which was gleyed and one not. The difference in the composition of the clays separated from horizons A180/10 and A180/13 (Table 2) is attributed to the effect of pronounced gleying conditions in the lower horizon. These results suggested that the elements most easily mobilized by gleying were Zn, P, Cu > Ni, Mn, and Fe, in that order. This of course assumes that the clay fraction of the two adjacent horizons would have had a similar composition in the absence of these restricted drainage conditions. Mineralogical analyses of the two fractions have shown that they are similar except for the lack of goethite in the lower horizon. As would be expected, the iron oxides have been readily broken down under gleying conditions. Some variations in the composition of the clay fractions with depth are expected but some of the changes ascribed to gleying in this profile are of such a magnitude that they are not considered to be due to this normal variation.

TABLE 2

Separated Clay Fractions from Two Horizons

Horizon	Al (%)	Fe (%)	P (%)	Zn (*p.p.m.*)	Cu (*p.p.m.*)	Ni (*p.p.m.*)	Mn (*p.p.m.*)
A180/10 . .	14·2	9·1	0·065	290	46	260	140
A180/13 . .	15·6	4·0	0·010	26	13	120	86

The above results are in agreement with Mitchell (1955) who has described a similar pedological effect for Co, Ni, Fe, V, Cu, and Mn in some Scottish soils of basic igneous origin. The low P content of soils developed under conditions of restricted drainage and their separated clay fractions is in agreement with the results of Glentworth (1947) and Williams and Saunders (1956). According to Robinson (1949), waterlogging, in the presence of organic matter, facilitates the mobilization of

Fe, Mn, Ca, and Mg but hinders the removal of the soluble products. In the area under study, the seasonal recession of the water-table and leaching have caused losses of the mobilized elements.

The mechanism of mobilization of these elements under gleying conditions is not a simple one. For some elements like Fe and Mn, reduction to more soluble, lower valence forms may be the dominant factor. For other elements such as Zn, Cu, and P, the breakdown of minerals such as goethite, under these conditions, may be important. Whereas P is probably associated with the goethite as adsorbed phosphate, the Zn and Cu may have isomorphically replaced the Fe in the mineral.

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CLAY MINERALOGY OF SOME AUSTRALIAN RED-BROWN EARTHS

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Summary

The clay mineralogy of Australian red-brown earths has been investigated by X-ray diffraction techniques supported by chemical analyses.

A brief description of the morphology of this group of soils is given, and their geographical distribution indicated. Profiles have been studied from each of the major areas in which red-brown earths are found.

A large number of samples were examined by X-ray diffraction. The results showed relatively little variation in clay mineralogy from one profile to another, or from one horizon to another within a profile. The dominant clay minerals in typical red-brown earths in southern Australia are illite and kaolin, but in Queensland kaolin predominates.

Chemical data (cation-exchange capacity, SiO_2:Al_2O_3 ratio) are consistent with the X-ray results. There is evidence, however, that the illites in these soils are deficient in structural potassium, having K contents between 2·5 and 4·1 per cent. K approximately. There is a consequent increase in the exchange capacity of these 'degraded' illites.

The variations in the clay mineralogy of these soils appear to depend mainly on the parent materials from which the soils are derived. Those red-brown earths developed on alluvial and similar materials contain more illite than kaolin; those soils developed on materials such as granite, granodiorite, and basalt contain mainly kaolin in the clay fraction.

PRESCOTT (1944) has discussed the distribution of red-brown earths in Australia, with special emphasis on South Australia, Victoria, and New South Wales. Representatives of the group are also found in Queensland. The suggested distribution is from tropical to sub-temperate regions over a range from 20° to 45° S. latitude. Prescott states that red-brown earths 'occur in zones of seasonal rainfall, whether of the Mediterranean type with rain in winter, or of the tropical type with rain in summer. At the height of the wet season, however, conditions are such that leaching is effective for a limited period.' These soils typically carry open savannah woodland vegetation, and are generally found in a zone with an annual rainfall between 14 and 25 in. The average daily mean temperature ranges from 60° to 75° F.

The morphology and chemistry of a number of red-brown earths from southern Australia have been described in detail by Piper (1938), Smith *et al.* (1943), Stephens *et al.* (1945), Smith (1945), Downes (1949), and Aitchison *et al.* (1954). The group has been compared with the reddish chestnut soils of the U.S.A. by Smith (1949) and Stephens (1950). Their relationship with other Australian soils has also been discussed by Stephens (1956).

Red-brown earths have a characteristic morphology. The A horizon is invariably brown to red-brown in colour, but may vary in texture from

sand to clay loam, with loams predominant. This horizon varies in depth from 6 to 24 in., but is commonly around 12 in. deep. There is a marked texture contrast between the A and B_1 horizon, which is always brighter and redder than the A horizon. The texture of the B_1 horizon is most commonly clay, but is occasionally sandy clay. The B_2 horizon consists of similarly-textured material, generally browner in colour and containing slight to large amounts of lime in soft or concretionary form,

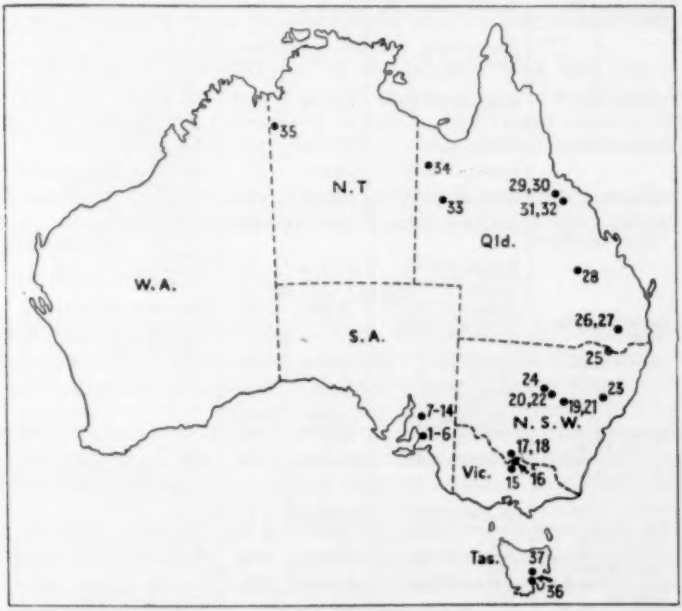

FIG. 1. Sketch map of Australia showing approximate locations of soils studied.

or both. The lime of the B_2 horizon usually persists into the C horizon. The C horizon, which often begins between 40 in. and 50 in. from the surface, consists of parent material of very diverse character. This may be either sedimentary or igneous rock, alluvium or colluvium, calcareous or non-calcareous. Chemical data reported by Piper (1938) for a number of red-brown earths in South Australia appear to correspond with data for red-brown earths from other localities, including those soils studied here.

Soil Profiles Studied

Soil samples taken from various horizons in 37 red-brown earth profiles have been studied. The geological origins of these profiles are described in Table 1 and their approximate geographical locations are shown in Fig. 1.

TABLE 1

Description of Some Red-brown Earth Profiles Studied

Profile no.	*Description*	*Approximate location*	*Soil no.*	*Leaching index*	*Parent material and reference*
1	Urrbrae fine sandy loam	Adelaide, S.A. (Waite Institute)	12721–6	1·18	Developed on an alluvial-colluvial apron derived mainly from adjacent Pre-Cambrian slates, shales, and quartzites. Aitchison *et al.* (1954).
2–6	..	Adelaide, S.A.	..	0·88	..
7	Light Pass fine sandy loam	Barossa Valley, S.A.	15144–9	1·01	Pleistocene to Recent proluvium derived from Pre-Cambrian calcareous rocks. Northcote *et al.* (1954).
8–12	..	Barossa Valley, S.A.	..	1·00	..
13	..	Clare, S.A.	3743–7	1·06	Developed on Pre-Cambrian shales, slates or schists or on alluvial material from same. Piper (1938).
14	Belalie loam	Booboorowie, S.A.	3805–9	1·06	On colluvial and older alluvial material; rocks of area are Pre-Cambrian in age. Piper (1938).
15	Lemnos loam	Dookie, Vic.	V6188–93	1·11	Fine-grained Tertiary alluvium. Downes (1949).
16	..	Barooga, N.S.W.	11423–8	1·11	Sedimentary material of river plains of western N.S.W.
17	Finley loam	Berriquin, N.S.W.	10300–8	0·68	Sedimentary fine channel deposits of 'prior streams'.
18	Deniboota loam light profile phase	Deniliquin, N.S.W.	13464–72	0·68	Solonchakous parent sediments laid down by 'prior streams'. Johnston (1953).
19	..	Trangie, N.S.W.	11700–4	0·70	Fine-grained alluvium.
20	..	County Narromine, N.S.W.	16204	0·59	On late Pleistocene alluvium.
21	..	Trangie, N.S.W.	16191	0·70	Fine-grained alluvium.
22	Summervale clay loam	Nyngan, N.S.W.	16168–73	0·59	Pleistocene alluvial deposits derived from metamorphosed Silurian sedimentary rocks.
23	Overton loam	Muswellbrook, N.S.W.	12891–5	0·97	Upper Coal Measures, Branxton Beds.
24	..	County Oxley, N.S.W.	17871–7	0·59	Pleistocene alluvium.
25	..	Dirranbandi, Qld.	16546	0·74	..
26	Oakey area red-brown earth	Jondaryan, Qld.	9887–9	1·12	Transported material, partly basaltic in origin.
27	Oakey area red-brown earth	Jondaryan, Qld.	16559–65	1·12	Alluvium of mixed origin, some from basalt, mostly from Mesozoic sedimentaries, silty and calcareous sandstones.
28	..	Springsure, Qld.	16886–90	0·91	..
29	Towers sandy loam (deep solum)	Charters Towers, Qld.	16554–8	0·85	Granodiorite mass intruded by some basic rocks as dykes.
30	Towers sandy loam (deep solum)	Charters Towers, Qld.	13156–9	0·85	On an acidic granite exposure.
31	Dalrymple sandy loam (*c*)	Burdekin Valley, Qld.	16549–53	1·25	Fine-grained basic igneous rock, probably of a dyke swarm through a granitic-dioritic mass.
32	Dalrymple loam	Lower Burdekin Valley, Qld.	14812–17	1·25	Low stony rises underlain by metamorphic sediments intruded by basic dykes.
33	Equivalent to Georgina r.b.e.	21° 48′ S., 138° 55′ E. (Kallala H.S.), Qld.	14020–3	0·38	Moderate textured basic alluvium.
34	Equivalent to Gulf Alluvial r.b.e.	On Riveraleigh-Lawn Hill Road, Qld.	14050–3	0·38	Basic alluvium.
35	..	17° 37′ S., 127° 37′ E. (Hall's Creek—Wyndham Rd.), N.T.	15546–8	0·53	Biotite granite.
36	Kimbolton clay loam	County Buckingham, Tas.	12022–5	1·69	Residual and colluvial material, from dolerite intrusion of Jurassic Age, in form of dykes and sills.
37	..	Brighton, Tas.	16943–7	1·69	Jurassic dolerite.

Soils selected by Dr. C. G. Stephens, Soil Survey and Pedology Section, Division of Soils, C.S.I.R.O.

Prescott (1949) has suggested the use of a climatic index as an indication of the leaching factor in soil formation. This index takes the form

$$P/E^m,$$

where P = annual rainfall in inches,

E = annual evaporation from a free water surface in inches,

and the value of the exponent m is determined experimentally. The best value of m appears to be about 0·75.

The values of this index reported in Table 1 have been calculated from data taken from *Climatic Averages, Australia*, prepared by the Bureau of Meteorology, Melbourne. There are meteorological stations reasonably close to most of the profiles studied. Profiles 1 to 24 in south-eastern Australia occur in climatic areas which are either cool with winter rains, or have moderate temperatures and uniform rains. The northern profiles, i.e. 25 to 35, are subject to moderate to high temperatures, with predominantly summer rains.

Several profiles were examined in the Adelaide area, and also in the Barossa Valley, S.A.; only one profile is described for each area, since the variation within a given area is small. Individual descriptions of relief have not been given since all the profiles studied are found on flat or gently sloping land.

The soils examined were chosen as typical red-brown earths, and included representative profiles from the major areas in which these soils have been mapped.

X-ray Studies

The X-ray diffraction methods used were similar to those described by Brindley (1951). Soil suspensions were prepared by dispersion, using sodium-hexa-meta-phosphate ('Calgon') and sodium hydroxide; no acid pretreatment was used during the dispersion procedure (Hutton, 1955). A clay-sized fraction ($< 2\mu$) was sampled by a pipette after a suitable sedimentation period. Care was taken to wash the pipette samples thoroughly before adding calcium chloride to Ca-saturate the clays; otherwise a significant amount of amorphous calcium phosphate may be precipitated with the clay fraction. Powder specimens (in cellulose-acetate tubes) and oriented-flake specimens were prepared from the suspensions; the flakes were usually saturated with glycerol. Where necessary various pretreatments were used (e.g. heating to 500° C.; H_2O_2 treatment for removing organic matter; reduction with H_2S to remove free iron oxide).

A 5·73-cm. diameter powder camera was used, in which there is no effective air-scatter up to 30Å. The minerals were usually identified by comparison with standard patterns set up in this laboratory.

Normal kaolin, illite, and montmorillonite were readily identified, but sometimes an oriented-flake (air-dry or glycerol-saturated) gave continuous central scattering from approximately 10Å up to 30Å (limit of camera). This cannot at present be ascribed to any particular mineral, and has been termed 'mixed-lattice minerals' in Table 2. This does not, however, preclude the possibility that the scatter is associated with minerals already identified, in particular with illite.

The results of the X-ray diffraction analysis of these soils (195 samples) are summarized in Table 2. These results are not reported in detail as most profiles show no significant variation in clay minerals with increasing depth. Furthermore the results from a number of profiles

are closely comparable, and hence are not recorded separately. Diffraction photographs show that many soils contain calcite, quartz, and iron oxide in small amounts. Generally the amount of well-crystallized iron oxide present is insufficient to identify it more specifically, though both

TABLE 2

X-ray Analyses of Some Red-brown Earths (< 2μ fraction)

Profile	*No.*	*Horizon*	*Depth (in.)*	I	K	M	M.L.	*Others*	*Comments*
1	12723	B_1	13–30	mod.	l.	..	..	Chlorite?	Chlorite increasing with depth.
2–6 Similar.									
7	15147	B_1	12–27	m.	mod.	..	l.	..	..
8, 9, 14, 21, and 24 Similar.									
13	3745	B_1	10–20	m.	mod.	..	l. to mod.	..	M.L. increasing slightly with depth, in general.
10, 11, 12, 15, 16, 17, 19, 20, and 22 Similar.									
18	13469	B	19–24	mod.	l.	l.	mod.	..	M. increasing with depth, but absent in surface soils.
23	12893	B_1	8–16	mod.	mod.	..	..	Chlorite or vermiculite?	..
25	16546	..	24–27	m.	mod.	l.	..	..	M. not well crystallized.
26	9889	B	18–33		m.	..	l.	..	Probably kaolinite.
27 Similar.									
28	16889	B	24–30	..	v.m.	?	l.	..	K. probably partly hydrated halloysite.
29	16555	B	6–18	l.	m.	..	l.	..	K. mineral similar to halloysite or 'fireclay'.
30	13158	B	13–19	..	m.	..	l.	..	K. probably halloysite.
31 Similar.									
32	14814	B_2	8–23	..	m.	..	mod.	..	K. probably halloysite.
33	14022	B	18–24	mod.	mod.	mod.	l.	..	M. increasing, and M.L. decreasing depth.
34	14052	BC	20–27	l.	m.	..	?	..	..
35	15548	BC	26–34	..	m.	mod.	l.	Chlorite or vermiculite (l.)	..
36	12024	B	8–13	..	..	mod.	l.	..	M. does not give very sharp basal spacing.
37	16947	B	9–18	..	l.	l.	mod.	..	K. probably halloysite.

I, illite; K, kaolin (specific minerals of this group identified where possible); M, montmorillonite; M.L., mixed-lattice minerals; v.m. very much, > 80%; m., much, 50–80%; mod., moderate, 20–50%; l., little, 10–20%; v.l., very little, 2–10%; tr., trace, 2% (these percentages very approximate); ?, identification doubtful.

haematite and goethite have been found in red-brown earths. These minerals are omitted from Table 2.

The X-ray results show that the dominant clay minerals in typical red-brown earths in South Australia, Victoria, and New South Wales are illite and kaolin, with the former representing from 40 to 60 per cent. of the < 2μ fraction (profiles 1 to 18). The dominant clay mineral present in the red-brown earths from eastern Queensland is kaolin, and this appears to be kaolinite in the south but a 'fireclay' or halloysite in the Charters Towers area. One soil from western Queensland, one from

Northern Territory and one from Tasmania contain montmorillonite as a major component.

Chemical Data

The cation-exchange capacities (at pH 8·4) for 90 soils have been obtained from the records of this Division. Data which were obviously affected by the presence of organic matter were disregarded in relating the cation-exchange capacity of the clay fraction of the soil to clay mineral composition. The method used to determine the sum of the metal ions and exchangeable hydrogen was essentially that described by Piper (1942). The data are given in a histogram (Fig. 2).

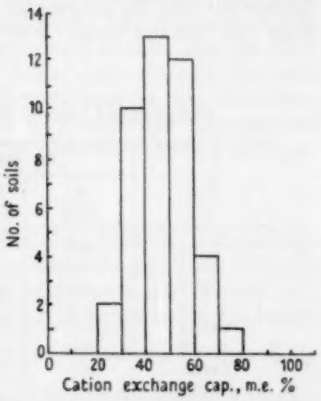

FIG. 2. Histogram of cation-exchange capacities (m.e. per 100 g clay) of some Australian red-brown earths. The data for two horizons only from any one profile are included here; they are taken from the records of the Soil Chemistry Section, Division of Soils, C.S.I.R.O.

These data are consistent with the X-ray results, since the presence of 'mixed-lattice' minerals (including 'degraded' illite) would raise the exchange capacities of both the soils which are illite-kaolin mixtures, and the soils which are predominantly kaolin, to values between 30 and 60 m.e. per 100 g. of oven-dry clay.

Piper (1938) has shown that the molecular ratios of SiO_2 to Al_2O_3 for the clay fraction of a number of red-brown earths in South Australia generally lie between 2·90 and 3·40. The present study has shown that for red-brown earths in the same area (including two profiles examined by Piper) the clay fractions are composed of 60–70 per cent. illite, 20–30 per cent. kaolin, and a little mixed-layer mineral. A mixture of 70 per cent. illite and 30 per cent. kaolin has a $SiO_2:Al_2O_3$ ratio of 3·10 approximately, and the X-ray analyses are therefore in general agreement with the chemically determined ratios of $SiO_2:Al_2O_3$.

Piper also reported that these soils show a strong correlation of K_2O content with the quantity (clay percentage $+\frac{2}{3}$ silt percentage). X-ray studies show that illite is the only mineral present in the clay fraction which contains potassium. The above calculation thus suggests that the proportion of illite in the clay fraction remains fairly constant since the ratio of silt to clay is usually below 1:4.

Potassium Content of Illitic Minerals in Some Red-brown Earths

Recently a number of workers (e.g. Grim *et al.* (1949), Vivaldi and Garcia (1955), and Droste (1956)) have reported finding 'degraded illite', which Grim (1953) describes as 'material which has been partially leached of its constituent alkalis and alkaline earths, but not sufficiently to transform it into new minerals'. Droste records that the X-ray pattern of such material shows 'asymmetry on the high side of the 10Å peak, and

the loss of this asymmetry in the heated and glycolated slide implies that some of the illite layers are now hydrated'. Such material should not show the further reflections which characterized either regularly or randomly interstratified minerals, but may show increased central scatter.

The potassium content of the illite described by Grim *et al.* (1937) lies between 5 and 6 per cent. If all illites contained this proportion of potassium then the potassium content of an illite-kaolin mixture should be directly proportional to the amount of illite present. Since illites appear to vary in potassium content, however, this direct relationship does not always hold. For illites in some solonized brown soils in

TABLE 3

Potassium Content of Illite in Some Red-brown Earths

	Clay fraction		*Calculations*		*X-ray*
Soil no.	*K* (%)	*Ex. Cap* (*m.e.* %)	*K in Illite* (%)	*Illite* (*y*) (%)	*Illite* (*y*) (%)
3745	2·1	46	3·4	61	70
3807	2·4	40	3·8	63	70
10302	2·2	39	3·9	58	70
11425	3·4	40	4·1	82	90
12893	1·7	34	3·8	43	50
13466	2·4	46	3·6	68	80
14051	0·7	40	2·5	30	25
12723	1·7	50	3·0	58	70

Cols. 2–5 were recalculated from data supplied by Mr. A. D. Haldane and Mr. J. T. Hutton, Division of Soils, C.S.I.R.O.

Australia, Norrish (1949) has suggested that the following approximate relationship holds between exchange capacity and potassium content:

$$\underset{\text{(m.e. per cent.)}^{\bullet}}{\text{potassium content}} + \underset{\text{(m.e. per cent.)}}{\text{exchange capacity}} = \text{a constant.}$$

This constant was of the order of 150 m.e. per cent. for illites in these soils, and has been assumed to be of the same order for the red-brown earths.

This relation was used as follows by Mr. A. D. Haldane† and Mr. J. T. Hutton† to determine the proportion (y) of illite, and also the potassium content (K_I) of this illite, in eight red-brown earths examined by X-ray diffraction by the author.

$$C_s = 20(1-y)+150y-K_s,$$
$$K_s = K_I \cdot y,$$

where C_s = exchange capacity of the clay sample,
K_s = potassium content of the sample in m.e. per cent.,
and 20 m.e. per cent. is accepted as the exchange capacity of kaolin.

The values obtained for K_I from the chemical data (Table 3) lie between 2·5 per cent. and 4·1 per cent. K. The values of the illite

• Milli-equivalents per 100 g. clay. † Chemist, Division of Soils, C.S.I.R.O.

content estimated from the X-ray patterns are included for comparison with values of y calculated from chemical data. The soils in Table 3 were chosen because their X-ray patterns indicate that they are essentially illite-kaolin mixtures showing only some central scatter in addition to the lines normally due to illite and kaolin. (It should be noted that the presence of moderate amounts of minerals other than illite and kaolin will invalidate the above approximate relationships.) The agreement between the two values of the illite content is reasonable for these soils, suggesting that they contain illite deficient in potassium.

Foster (1954) has emphasized that removal of potassium from illite does not immediately change it to montmorillonite. It is therefore not unreasonable to suppose that some illites occurring in soils may give the standard illite pattern without additional lines, even though they are partially leached of potassium. The above results suggest that this is the case for some Australian red-brown earths. The exchange capacities of such illites will be rather higher than that for illite containing 5 to 6 per cent. potassium.

Pedogenesis

The two principal factors influencing the clay mineral composition of these soils are parent material and climate, since the drainage status is uniformly good for the red-brown earths. Of these the climate will probably be the less important. Prescott (1949) suggested that the index $\frac{P}{E^{0.75}}$ assumes values* between 0·74 and 1·43 for red-brown earths. This study has shown that for red-brown earths in South Australia, Victoria, New South Wales, and eastern Queensland (profiles 1 to 32) the leaching index $\frac{P}{E^{0.75}}$ ranges from 0·59 to 1·25. It is interesting to observe that all these soils have values of Prescott's leaching index within the same range, even though the average daily mean temperature and the annual rainfall figures are somewhat higher in eastern Queensland. Variations in the clay mineralogy of red-brown earths in these areas (which are the major occurrences of this soil group) do not, therefore, appear to be due to variations in climate from one profile to another.

On casual inspection of the X-ray data the proportion of kaolin in the $< 2\mu$ fraction appears to increase with mean annual temperature. On closer examination, however, this is seen to be due to a fortuitous correlation between mean annual temperature and parent material.

Parent material is undoubtedly the main factor in determining the clay mineralogy of Australian red-brown earths. Those soils which are formed on the alluvial, sedimentary, and/or loessial deposits of the river plains extending inland from the Mt. Lofty Ranges in South Australia, and from the Great Dividing Range in Victoria and New South Wales, have clay fractions which are very largely mixtures of illite and kaolin. The relative proportions of the two minerals are fairly constant, both

* Prescott (1949) used an exponent $m = 0{\cdot}70$, giving limits 0·92 to 1·70 for these soils. He has since recommended $m = 0{\cdot}75$ as a better value, and for this exponent the limits are approximately 0·74 and 1·43.

within a given profile and from one profile to the next. Red-brown earths formed on other parent materials—granite, granodiorite, basalt, basaltic alluvium—show quite different clay mineralogy. Kaolin is the dominant clay mineral of these soils, whereas illite has not in general been observed as a major component. This is probably because these parent materials are unable to contribute sufficient potassium for the formation of illite.

Profiles 33 to 37 need further discussion. The two profiles in western Queensland (33 and 34) show some illite, and 33 shows montmorillonite. These soils have the typical morphological features of the red-brown earth group. Their parent materials ('basic alluvium') are not known precisely enough to explain the presence of illite, which is rather unexpected; but they must contribute a little potassium during weathering, which is not removed by the lower than usual degree of leaching these two profiles experience.

After the X-ray data were obtained the field descriptions for profiles 35 to 37 were re-examined, and it was found that all three soils are doubtful red-brown earths. The northern profile 35 was sampled in an area where there are no soils with clearly defined texture contrasts, though red earths and skeletal red soils are reported. The two Tasmanian soils, 36 and 37, which Prescott (1944) mapped as red-brown earths, have recently been remapped as brown earths. They also have leaching indices significantly higher than is usual for red-brown earths. It is therefore interesting that of the thirty-seven profiles studied these two alone contain only a little kaolin and in addition do not contain illite at all.

Practically all of the profiles examined show clay-mineral compositions which are fairly constant with increasing depth. The climatic and leaching conditions under which the red-brown earths are generally formed apparently have been insufficient to cause much weathering of the clay minerals in the profile even though they have caused the profile development.

It is not possible from the results of the present study to relate the clay mineralogy of the particular red-brown earth profiles more closely to their parent materials than has been attempted here, since the original samples did not include samples of the parent materials. In addition the sediments, &c., which form the parent materials of many red-brown earths are themselves ill defined and heterogeneous.

Acknowledgements

The author acknowledges with thanks the advice and assistance of various officers of the Division of Soils during the course of this work, particularly Mr. J. K. Taylor, Dr. K. Norrish, and Mr. J. T. Hutton for helpful criticism, and Mr. J. Pickering for technical assistance in the X-ray studies.

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AN EXAMINATION OF THE METHOD OF AGGREGATE ANALYSIS BY WET SIEVING IN RELATION TO THE INFLUENCE OF DIVERSE LEYS ON ARABLE SOILS

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Summary

Wet sieving as a measure of the effect of leys on crumb stability is discussed, briefly noting the significant details of sampling and analysis.

The increase in water-stable aggregation following several ryegrass/white clover leys of four years duration was of the same magnitude for both clay and sandy loam soils. The lighter soil, having the lower initial stability, showed the greater proportionate increase. Perennial ryegrass/white clover swards were consistent in giving higher values for water-stable aggregation than other commonly sown grasses. It would seem that a large proportion of clover in a sward would not impair the stabilizing effect of a ley. There was no evidence of any significant variation resulting from different methods of grassland utilization. Data from Hurley soil suggest that intensive grazing did not reduce the effect of the grass ley on soil stability as long as a plant cover was maintained. Cocksfoot sown in drills for seed production had less effect on the soil than did swards of this grass sown with white clover. The application of nitro-chalk to grass leys over a three-year period at annual rates up to 16 cwt. per acre had no significant effect on either of the soils examined. Profiles to 1 ft. depth showed that, whereas the high stability found under permanent pasture extended throughout this profile, the increase in water-stable aggregation under a three-year ley was largely confined to the top few centimetres.

THERE would seem to be no single technique which makes possible a comprehensive examination of the effects of grass leys on soil physical conditions. Whilst aggregate analysis will measure changes in certain physical properties of an arable soil following a few years under grass, an appraisal of the significance, both statistical and agricultural, of such variation in crumb stability requires examination of the influences of other factors upon the analytical values obtained. For this reason Part I examines the pattern of variability in the results of aggregate analysis that may be ascribed to variation in inherent soil properties, time and method of sampling, and details of analysis. Against this pattern of variability must be viewed the effects which may be attributed to the ley, its species composition, management, and manuring; some account of these appears in Part II.

I. *Sources of Variation in the Results of Aggregate Analysis other than Effects Attributable to the Ley*

The water-stability of aggregates as determined by wet sieving is widely used as an index of the structural stability of the soil. It has been frequently employed to follow changes in soil condition resulting from agricultural practices, and particularly in studying the contrasting influence of perennial herbage cover and annual tillage (Martin, 1944; McHenry and Newell, 1947; Williams, 1949; Low, 1955). Methods of

analysis vary more in manipulative detail than in principle. Nevertheless, variations in the routine of sample preparation and analytical procedure influence the values obtained and to some extent the interpretation of the results (see Section A). Soil variability is specific for a particular field and design of experiment, and field sampling procedure must ensure that a representative sample be obtained. Although for certain comparisons the rigid application of an experimental design may be impossible some estimate of the error associated with field sampling and analysis should be made. Some of the more important sources of variability in the values obtained for field plots are discussed in Section B.

Laboratory preparation of sample and method of analysis

Field samples in a suitable moist condition are broken to pass through a sieve of ½-in. square mesh. Stones exceeding this size are discarded. Soils are then dried on shallow trays in a fan-ventilated oven at 30° C. for four days and subsequently stored in waxed cardboard cartons with screw-on lids until required for anlysis. Four 50±5 g. sub-samples are taken from each field sample with a dividing hopper. Each sub-sample is poured into a gas jar containing about 900 ml. demineralized water, the total volume then being made up to 1 litre. The jar is stoppered, inverted, and reinverted and allowed to stand undisturbed for 30 minutes. After this period the jar is mechanically rotated 15 times in 1 minute. The contents of the jar are then transferred to a sieve of 6-in. diameter and sieved by hand under water. A 0·5-mm. round mesh sieve is used for light soils, and 2·0-mm. and 0·5-mm. mesh sieves are used separately and in that order for heavy soils. The sieving is standardized by rotating the sieve under water and laterally oscillating four times at each of twelve points at 30° intervals. Aggregates, stones, and organic materials remaining on the sieve are transferred to a glass dish and dried at 100° C. and weighed. The aggregates are then dispersed with H_2O_2 and NaOH, resieved and after drying the weight of stones and organic matter retained on the same mesh as used for analysis is deducted from the initial weight. Results are expressed as grammes of water-stable aggregates greater than 2·0 (or 0·5) mm. diameter per 100 g. air-dried soil.

A. *Sources of error in sub-sampling and analysis*

(i) *Sieving the field sample before drying.* Although fineness of division is conducive to accurate sub-sampling it is difficult, without compression and puddling, to pass moist soil containing roots through a sieve with appreciably less than a ½-in. mesh. When examining soils from grass leys showing considerable profile variation both in stability, granulation, and moisture content (see p. 262), any technique which discards an appreciable fraction of the field sample on a dry-crumb size basis is not fully acceptable. For this reason the whole sample, which has passed through the ½-in. mesh sieve, is retained for analysis.

(ii) *Drying the field sample.* The immersion of air-dry soil in water

magnifies the forces of slaking and the initial moisture content of the sample, even within the air-dry range, is critical. The influence of the initial moisture content on the estimation of water-stable aggregates is illustrated in Fig. 1 where an increase of soil moisture from 4 to 6 per cent. increased the value for water-stable aggregates from 10 to 15 per cent. respectively.

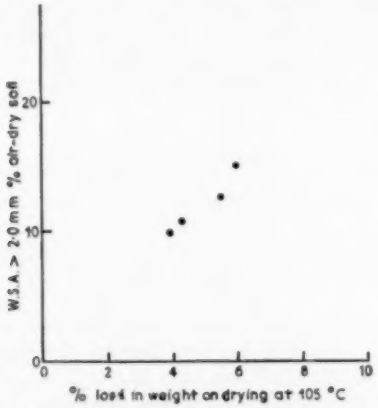

FIG. 1. Variation with increasing moisture content in the water-stable aggregation of the same soil.

When the moisture contents of the samples are known the effect of variation may be removed from a series of values by an analysis of covariance. For a series of values in which the moisture content only ranged from 5·25 to 6·25 per cent., the standard error of the per cent. by weight of water-stable aggregates $> 2{\cdot}0$ mm. was appreciably reduced by covariance correction.

	% *W.S.A.*
Not corrected for varying moisture content . . .	$10{\cdot}36 \pm 1{\cdot}89$
Corrected for varying moisture content . . .	$10{\cdot}34 \pm 1{\cdot}25$

This technique may be of value if drying conditions cannot be closely controlled, but suffers from the objection that the varying moisture content of a soil at any given vapour pressure may be a legitimate component of its stability to wetting.

(iii) *Rate of wetting*. In principle much has been suggested concerning the relative merits of wetting soils by immersion, under tension or in a vacuum prior to wet sieving. In practice wetting by immersion is most rapid and convenient and, as pointed out by The Committee on Physical Analysis (1953), most easily standardized. Wetting dry crumbs by raindrop impact was found by Pereira (1955) to give a better relationship with other soil properties than did wetting under vacuum. Depending upon the nature of the rainfall, its drop size, intensity, and duration, a varying proportion of the soil *surface* will suffer rapid wetting in the immediate vicinity of raindrops. That such rapid wetting accounts for

some considerable proportion of the deterioration of tilth would agree with observation (Low, 1954) that the results of wetting soils by immersion more closely correspond with the structural appearance of soils in the field than do the results of wetting under slight tension.

(iv) *Mechanical dispersion.* The main mechanical component of aggregate dispersion is standardized by shaking the soil in water. A general purpose end-over-end type of shaker is employed with a holder taking gas jars 16 in. long and 3 in. internal diameter. The jars are

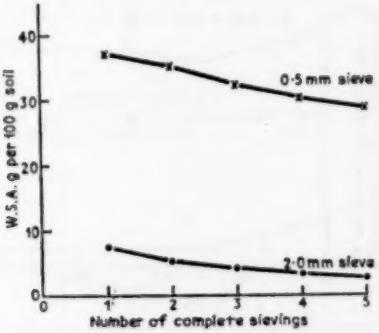

FIG. 2. Decrease in water-stable aggregation induced by repeated sieving.

marked at the 1-litre level and soil plus water made up to this level before shaking. Although the total capacity of a set of jars as purchased varied from 1·6 to 1·8 litres the resultant variation in the air suspension ratio did not measurably affect the degree of soil dispersion. Recently Williamson *et al.* (1956*a*), using a slow wetting and a mechanical sieving technique, recorded values for water-stable aggregation similar to those obtained in this laboratory for the same soils.

(v) *Wet sieving.* This is a grading process which separates those soil units above a selected size which have proved resistant to the forces of slaking and mechanical action induced by previous treatment. However, some further mechanical dispersion does occur as a result of wet sieving, and as shown in Fig. 2 increasing the sieving action by multiples of two to five reduced the weight of material retained on the sieve. Hand sieving is rapid but may only be employed therefore when the total dispersive forces of the analysis are large compared with the mechanical component attributable to the action of wet sieving.

(vi) *The choice of aggregate size.* Results of aggregate analysis obtained by wet sieving are considered to be a relative measure of crumb stability: the sieved fractions do not represent the size distribution of water-stable crumbs present in the soil. The only significance of mesh size, therefore, is in relation to the precision with which change in crumb stability is estimated. This requires that about one-tenth of the soil sample should be retained on the sieve: a 2-mm. mesh has been found the most appropriate for stable clay soils and a 0·5-mm. mesh for sandy loams.

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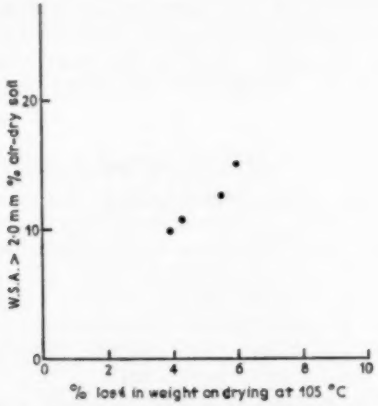

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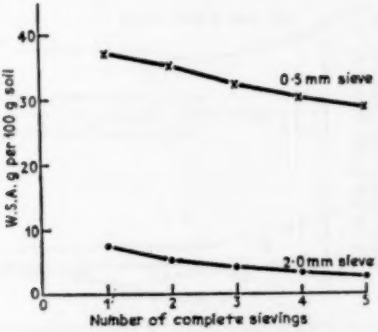

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B. *Sources of variation in the field sample*

(i) *Variation between replicate field plots.* This source of variability is largely specific to a particular field and design of experiment. Drainage (Low, 1955) and clay content (Clarke, 1948; Hubbell, 1951) have been cited as factors which may influence the aggregate stability of a soil subject to uniform agricultural management. Comparison of the relative stability of arable soils over a wide textural range (Fig. 3*a*) confirms the significance of clay content when comparing soils from different farms

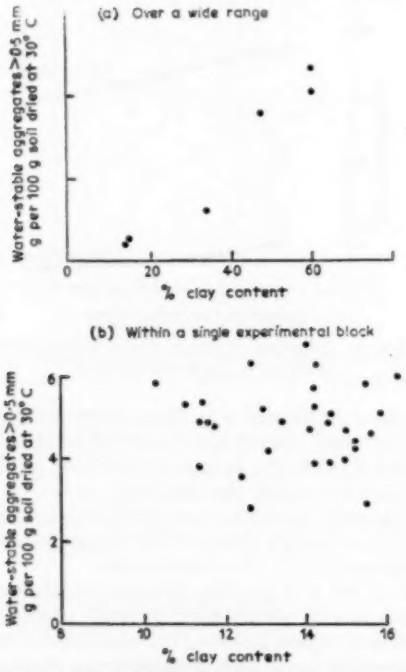

FIG. 3. Relationship between clay content and water-stable aggregation of arable soils.

or even, as at Hurley, from different fields. However, it will be seen in Fig. 3*b* that, within the confines of a single experimental block, although the clay content varied from 10 to 16 per cent., the contribution of this factor to the total variation in aggregate analysis was insignificant.

(ii) *Seasonal variation.* The seasonal variation in content of water-stable aggregates was observed by bi-monthly sampling of three sites. All were on the same soil series with a clay content of 35–40 per cent., but the organic content varies considerably, being closely correlated with water-stable aggregation. There is evidence of a smooth seasonal change (see Fig. 4) in general form similar to that reported by Wilson (1947). The total seasonal variation for all plots is significant ($P = 0{\cdot}001$).

Rennie *et al.* (1954) observed a similar seasonal pattern and found that values for water-stable aggregation fluctuated in relation to environmental conditions which might be expected also to influence microbial activity.

(iii) *Depth of sampling.* The choice of sampling depth is limited by two considerations. From the data given in a later section it is apparent that effects due to a three-year grass ley will be most pronounced in a shallow

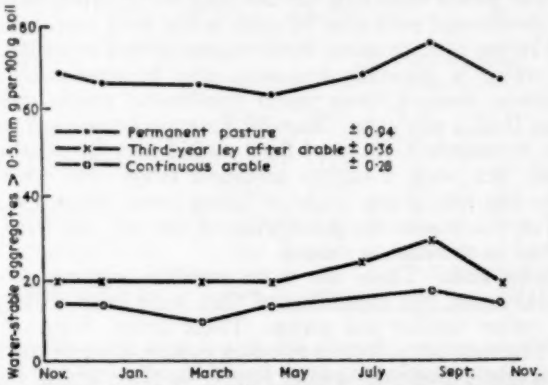

FIG. 4. Seasonal variation in the water-stable aggregation of field plots under three systems of husbandry.

sample. However, if such effects are to be followed through an alternate husbandry cycle the sample must be taken at least to plough depth. For these reasons sampling and ploughing depth have been standardized at 6 in. Bias, occasioned by changes in volume weight due to cultivations and possibly frost heave, is minimized by sampling at least six months after ploughing and always in autumn.

II. *The Influence of Leys on the Development of Aggregate Stability in Soils*

The development of water-stable aggregates, over a period of years from sowing, has been investigated by Low (1955) on a wide range of soil types. This author presents data illustrating the low annual quantitative increase in stable aggregates and the low rate of increase in aggregation even when the potential aggregation of a soil was high. Williamson *et al.* (1956) have reported on the changes in the content of water-stable aggregates during six- and eight-course rotations containing respectively three- and four-year leys. Pringle and Coutts (1955) report that species and strains of grasses and white clover exhibit differences in their effect on the development of stable aggregates. Martin (1944) and Pereira *et al.* (1955) have demonstrated the influence of perennial grasses and cover crops on the content of water-stable aggregates in East African soils and Barley (1953) that of perennial pasture under irrigation.

The investigations reported here deal with the development of water-stable aggregates under three- or four-year leys, on two soil types. It has been possible to compare the aggregate development as affected by

species and strains of grasses, and by some management and fertilizer practices.

The soil types will be labelled Drayton or Hurley and unless a note is made to the contrary only soil series corresponding to the following description will be considered.

The Drayton soils. These are of Lower Lias parentage with some local drift. They are characterized by a clay content of 50 to 60 per cent. Fragments of parent limestone are normally to be found throughout the cultivated profile and soils may be quite stony, with a calcium carbonate content of 10 per cent. or more, in the region of rock outcrops, where the drainage, which is generally impeded, may be reasonably free. The organic carbon content, even under continuous arable cultivation, is seldom less than 2 per cent. Angular structural units are strongly developed in the sub-soil. A good frost mould may be developed in the surface soil, but, with a narrow moisture range over which effective cultivations can take place, areas of spring sown crops are necessarily limited. For this reason the granulation of the soil, apparent when leys are ploughed in summer, is valued.

The Hurley soils. These are more variable, making generalization difficult. However, the experimental data have been mainly obtained from two rather similar soil series. These series, lying on a plateau above the Thames valley, form a complex pattern even within the limited area of a single experiment owing largely to the varying depth of the Upper Chalk which underlies these soils. When the chalk lies at a depth of a foot or less the clay content of the surface soil may rise to 17 per cent. and the pH to about 8. Within a few dozen yards the chalk may be at a depth of 10 ft. and a sandy material, possibly of Reading Bed origin, dominates soil texture and reaction. In such areas the clay content may fall to 10 per cent. and the pH to 5. The silt content of these soils varies rather less than the clay; from about 7 to 10 per cent. Fragments of flint and some pebbles are common. Under prolonged arable cultivation organic carbon content to plough depth varies in relation to the texture, from about 0·9 to 1·5 per cent. Field observation provides evidence of structural instability. Thus, the soil when dry becomes very hard and compact with an angular fracture and an indication of horizontal stratification; wheel marks on arable land will hold water after rain although the sub-surface drainage is free. The surface structure of a seed bed frequently shows fusion and slumping of the soil units. However, over quite a wide range of conditions cultivations can be expected to produce a reasonable tilth. Under the action of frost the surface soil develops a fine powdery structure.

Field experiments. Data have been collected from a number of field experiments. The plot size varies from 0·05 to 0·03 acre, the majority being of the latter size. All the experiments are of randomized block design with plots in several cases split for species, management, or manuring comparisons. The greater accuracy with which split treatment effects can be estimated has proved of particular value for soil measurements. Experiments used for soil studies at Hurley are replicated in time.

Results

Increase in water-stable aggregation under three-year leys. Results from several experiments all with perennial ryegrass/white clover are given in Table 1.

TABLE 1

Water-stable Aggregation of Arable Soils Before and After Three-year Leys Sown to Perennial Ryegrass/White Clover Swards.
(*g. per 100 g. air-dry soil*)

	Year of sampling		*Age of sward when sampled*		
	Initial	*Final*	*½ yr.*	*3½ yrs.*	*Increase*
			Aggregates > 0·5 mm.		
Hurley soil experiment H9	1951	1954	3·2	8·2	5·0±0·4
	1952	1955	2·5	6·5	4·0±0·4
,, ,, experiment H16	1951	1954	3·4	8·8	5·4±0·6
	1952	1955	1·8	5·8	4·0±0·7
Drayton soil experiment E127	1949	1953	41·8	45·1	3·3±2·0
			Aggregates > 2·0 mm.		
,, ,, experiment E127	1949	1953	2·1	5·8	3·7±0·7

It has been found in experiment H9 that the values obtained for the initial sampling (the lapse of about six months after seeding allows for soil compaction) are indistinguishable from the values for the water-stable aggregation of plots which were retained under an arable four-course rotation and which carried a crop of barley during this period. The leys have significantly increased the quantity of water-stable aggregates greater than 0·5 mm. in both sites at Hurley and that of aggregates greater than 2 mm. at the Drayton site. The latter demonstrates that greater significance may be obtained, in the case of stable soils, by the use of a large size mesh (a point made in the section on the choice of sieve mesh).

Despite the greater stability of the Drayton soil in the arable condition the quantitative increase in water-stable aggregation following a three-year ley is of the same order as shown by the Hurley soils.

Comparison can be made between the E127 ley and the stability of a similar soil under a ryegrass/white clover dominant permanent pasture at Drayton. Sampled to 6 in. depth this permanent pasture gave 68 per cent. water-stable aggregates > 0·5 mm., about two-thirds of this material being retained on a 2·0-mm. mesh.

The effect of different grasses on water-stable aggregation. In Table 2 data are examined from a number of field experiments. Three cases occur (E114, E51, and H15) of data taken from paddocks in the same field but with no replication. The standard error includes all sources of random deviation and is calculated from the appropriate error mean square.

Ryegrass swards are associated with the greatest values for water-stable aggregation on both soils. This is most clearly shown in a comparison of ryegrass with cocksfoot. The effect on crumb stability of

timothy and fescue cannot be significantly differentiated from that of cocksfoot. The sown species and strains are given in col. 1 and although there was some intrusion of unsown grasses this was negligible in the swards sown to a mixture of grasses and clover. There was a heavy

TABLE 2

The Influence of Sown Grasses and Clover on the Development of Water-stable Aggregates under Leys

	Drayton soil				*Hurley soil*			
Experiment No.	E77	E127	E114	E51	H9	H16	H8	H15
Date sown	1947	1949	1948	1946	1950–1	1951–2	1951	1950
Date sampled	1951	1953	1952	1952	1953–4	1954–5	1955	1953
Swards	% W.S.A. > 2·0 mm.				% W.S.A. > 0·5 mm.			
Perennial Ryegrass:								
S24	..	..	..	..	..	8·3	..	..
S24 + White clover S100	13·1	..	20·4	..	..	7·3	7·5	6·4
S23 + White clover S100	..	5·8	15·5	..	8·6	..	6·2	..
Cocksfoot:								
S37 + White clover S100	9·5	..	..	13·6	7·1	5·4	6·4	..
S143 + White clover S100	..	3·4	15·0	..	..	..	..	4·0
Timothy:								
S51 + White clover S100	..	4·6	..	..	..	..	..	..
S48 + White clover S100	8·5	..	..	14·6	..	..	7·0	..
S48 + Red clover S123	..	..	..	..	..	5·8	..	..
Meadow fescue:								
S53 + White clover S100	..	3·9	..	15·6	..	..	..	..
S53, S215 + White clover S100	..	..	..	..	..	..	5·4	..
Red fescue:								
S59 + White clover S100	..	..	..	..	..	..	6·4	..
White clover:								
S100 + S184	..	..	..	..	..	6·8	7·7	..
S100	..	..	..	..	..	..	..	5·8
Standard error	1·25	1·02	Paddock	Paddock	0·43	0·47	1·5	Paddock
Error degrees of freedom (*n*)	4	6	..	..	15	12	6	..

intrusion of grass, mainly *Poa* species, into the plots sown to white clover alone in experiments H16 and H8. The clover paddock in H15 was relatively free of grasses when sampled. It would appear that white clover is not materially inferior to grasses in its effect on crumb stability.

TABLE 3

Sward Utilization and Water-stable Aggregates (W.S.A. > 0·5 mm.; g. per 100 g. air-dry soil)

Experiment	*H9*	*H8*
Frequent rotational grazing	8·1	..
Infrequent rotational grazing	8·3	6·8
Hay and aftermath grazing	7·3	6·2
Herbage cut and removed	7·8	..
Standard error	0·6	0·3
Error degrees of freedom	15	14

The effect of sward utilization on soil stability. The results of two experiments are given in Table 3 showing the effect of sward utilization on the aggregation of Hurley soil.

The treatments had been applied throughout the life of the leys, three years and four years respectively for experiments H9 and H8. In the former experiment the swards were cocksfoot/white clover and perennial ryegrass/white clover but in the latter experiment fifteen

swards of differing grass species composition contribute to the values shown.

Experiment H8 provided some evidence of an appreciable interaction between the effect on water-stable aggregation of the very diverse sward composition and management. When only those grasses commonly

TABLE 4

Water-stable Aggregation of Soil under Drill Row Crop of Cocksfoot and Cocksfoot/White Clover Swards (g. per 100 g. air-dry soil)

	Drayton soil	*Hurley soil*
Experiment	E117	H16
W.S.A. greater than	2·0 mm.	0·5 mm.
Soil directly beneath row	4·3	5·9
Soil midway between row	1·8	3·7
Cocksfoot/white clover sward, grazed	..	6·2
Arable, at time of sowing grass crops	..	3·9

sown in leys were taken into account (the swards for which data were given in Table 2) the mean of the grazed plots was 7·8 and that of the hayed plots 5·5. This effect of management on water-stable aggregation, within the confines of swards consisting of the grasses commonly used in seeds mixtures, was highly significant.

The stability of soil under and between widely spaced cocksfoot rows. For purposes of seed production it is a practice to sow cocksfoot and some other grasses in drills some 2 ft. apart; any improvement in soil conditions may be considered a valuable by-product of these crops.

TABLE 5

The Effect of Nitrogenous Fertilizer on Water-stable Aggregates (g. per 100 g. air-dry soil)

	Drayton soil		*Hurley soil*			
Aggregate size greater than	2·0 mm.		0·5 mm.			
Nitro-chalk per acre per annum	Nil	8 cwt.	Nil	4 cwt.	8 cwt.	16 cwt.
Perennial ryegrass/white clover	6·0	5·7	8·3	8·6	9·0	8·6
Cocksfoot/white clover	4·3	2·6	7·1	7·4	7·6	6·6
Timothy/white clover	3·9	3·9	..	..	..	..
Meadow fescue/white clover	4·5	4·6	..	..	..	..
Mean	4·7	4·2	7·7	8·0	8·3	7·6
S.E. mean	0·44		0·60			
Error degrees of freedom	8		15			

In Table 4 water-stable aggregation is presented for soil taken from beneath and from between rows of cocksfoot. For comparison the values obtained from a cocksfoot/white clover sward are given for plots within the same experiment at Hurley. The results from the two soils are essentially the same. The grass drill crop had little effect on the soil

aggregate stability between the rows. From under the grass rows the soil had almost the same aggregate stability as that of the cocksfoot/white clover sward of the same age.

The effect of nitrogenous fertilizing of leys on water-stable aggregates. The results are given in Table 5 from one experiment on each of the Drayton and Hurley soils; at both sites nitrogenous fertilizing had been practised for three years. This treatment depressed the white clover and increased the grass growth and at the highest level used, 16 cwt. per acre per annum, clover was virtually eliminated from the sward by the luxuriant growth of the grasses. However, the use of nitrogenous fertilizer did not significantly affect water-stable aggregation.

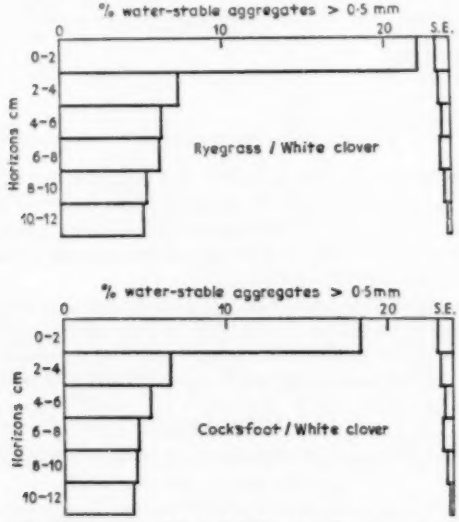

FIG. 5. Profile in an arable soil following three years under ley.

Variation in aggregate stability within the topsoil profile

Data from sixteen field plots are summarized in Fig. 5. The profiles are to 12 cm. depth; that is within the plough-zone of this old arable soil. Two neighbouring fields, one under permanent pasture and the other under annual tillage, provide profile data suggesting that the soil under pasture has greater aggregate stability extending to at least 12 in. depth. The shallow influence of the ley is in marked contrast. This agrees with Emerson (1954*a*), who further concluded that the main difference between a four-year ley and permanent grass was the depth to which improvement in crumb cohesion extends. It is apparent that the soil under the ley has within the top centimetre or so developed a high degree of crumb stability compared with the mean change observed to plough depth. The species effect, previously discussed with reference to samples taken to 6 in. depth, is also considerably magnified in the top horizon.

Discussion

The majority of the results appertain to structural changes brought about by three- or four-year leys sown on arable land and they indicate that although there is a distinct increase in water-stable aggregation during these periods the degree of improvement is relatively small in relation to the conditions found under old permanent grassland. These observations are in agreement with those of Low (1955) who considered that, except for very sandy soils, many years under grass are required to restore arable soils to the structural condition found under old grassland. Comparing the 0·5 mm. fraction the increase in the quantity of soil aggregated under the leys on the Hurley and Drayton soils is remarkably similar (see Table 1) considering the greater inherent stability of the latter soil. There is thus little evidence of any interaction between wide variation in soil texture and the stabilizing influence of the ley.

The effect of individual grasses on the development of water-stable aggregates has been mainly observed in swards containing white clover. The superiority of perennial ryegrass over cocksfoot has been consistent in all the experiments both on the Drayton heavy clay soils and on the Hurley sandy clay loams. These results are contrary to those of Pringle and Coutts (1956) who reported that water-stable aggregation under S23 perennial ryegrass was inferior to that under S37 cocksfoot; Barley (1953) investigating the relative effects of these two grass species on irrigated soils in Australia also found that cocksfoot gave the greater water-stable aggregation. From our results the relative influence in water-stable aggregation of the other two perennial grass species of importance in seeds mixtures used in Britain, timothy and meadow fescue, is indeterminate. McHenry and Newell (1947) found that of three cool-season grasses, smooth-stalked meadow grass, bromegrass, and cocksfoot, the last was associated, after seven years under ley, with the lowest water-stable aggregation. No data are available at Hurley for bromegrass but the other two species, in combination with white clover, have been examined; the quantity of water-stable aggregates greater than 0·5 mm. per 100 g. of air-dry soil was 7·4 and 5·6 for smooth-stalked meadow grass and cocksfoot respectively—a result which is in agreement with that of McHenry and Newell.

It would thus appear that although grass species differ in their influence on the development of water-stable aggregates in a particular situation, these differences are small and require detailed investigation to show statistical significance.

Low (1955) reported that root development of a grass/clover sward is enhanced by improvement in soil structure. Data show that perennial ryegrass under a variety of management treatments develops a greater mass of root material than cocksfoot (Grassland Research Institute, 1956). Moreover, the root material developed under these two swards has not been materially affected by either the manner in which the swards were used or by the application of nitrogenous fertilizers: this was also the case in respect of soil aggregation. Thus, the root development of the grass sward and water-stable aggregation are closely parallel. It is suggested that it is the greater root development of perennial ryegrass,

compared with cocksfoot, in leys of three or four years duration, which caused the differences observed in soil aggregation.

Kennedy and Russell (1948) found that the specific gravity of the surface soil increased with the frequency with which the sward was clipped. Kadelin (1952) considered that grazing reduced aggregation although pseudo-aggregates could be formed by compaction. Such aggregates would not, he thought, be resistant to prolonged wetting. Low (1955) maintains that by compaction of the soil, grazing may restrict root development and consequently greater water-stable aggregation is found following swards cut for hay. The results presented here do not indicate any significant difference in water-stable aggregation of soil arising from grazing, hay and aftermath grazing, or cutting only. It should be observed that grazing was not practised during the winter months. Frequent grazing, which involved ten grazings between April and October, had the effect of considerably reducing herbage yield compared with grazing six times during the same period (infrequent grazing). However these managements, and others, did not differentially affect root growth or water-stable aggregation (Table 3). Only ley treatments affecting root weight, namely grass species, influenced the development of water-stable aggregates in the soil. There is no evidence that the treading of grazing animals, at the intensity necessary for the full utilization of the grass grown, reduces the development of water-stable soil aggregates.

Agricultural systems involving alternate husbandry impose a series of forces upon the surface soil differing widely in character and in the span of time over which they operate. During the grassland phase the surface soil (referring to the top centimetre or so) is protected both from severe desiccation and slaking and from raindrop impact but is subject, over a wide range of moisture conditions, to the mechanical effect of treading. It has been found that the crumb stability of this shallow surface horizon may be greatly increased by a three-year ley (Fig. 5*b*) and it is suggested that the dangers of poaching the sward may be correspondingly reduced.

In contrast, under the arable break bare soil will be exposed for considerable periods of the year to alternate desiccation, slaking, and the mechanical action of raindrop impact. Ploughing the ley will bury the well-aggregated and stabilized topsoil and bring to the surface material little affected, in terms of water-stable aggregation, by the preceding grassland. When the plough layer is mixed by subsequent cultivations, the water-stable aggregation of the surface soil will depend upon the depth of ploughing in relation to the profile characteristics and magnitude of the increase in water-stable aggregation effected by the ley. The values given in this paper for the change in water-stable aggregation due to diverse leys are for samples taken to 6 in. depth and indicate the change in stability of the surface soil when the sward is ploughed to this depth and the furrow slice thoroughly mixed.

The variation between swards of differing species composition, consistent over a number of years and on two contrasting soils, strongly suggests a real difference in the ability of commonly sown grasses to affect soil conditions. At present there is probably little reason for attaching

any agricultural significance to these differences. When studying the effect of the species composition of a sward it is necessary to consider factors which may differentially affect the vigour and density of the individual plants. Of these factors neither diverse systems of sward management nor varying levels of nitrogenous manuring have appreciably affected the increase in water-stable aggregation of soils under three-year leys. Over a longer period of treatment, if only because of variation in the species composition of the sward, management and manuring may be expected to have an increasing effect.

Under intensive grazing, soil compaction is expected to be most severe, whereas it will be minimized when the herbage is cut and removed from the plot by hand. The hypothesis that soil compaction may limit the depth and extent of the increase in water-stable aggregation of a soil initially poor in structure is unsupported: plots subject to intensive grazing on the one hand and infrequent cutting on the other show very similar increase in aggregate stability (Table 3). Finally, if aggregate analysis is of any agricultural significance it is necessary to postulate a level at which crumb stability may limit crop production (or increase costs). If a critical level exists it may be expected to vary with the crop, the cultivation sequence employed and with the relative position of other potentially limiting factors—nitrogen, mineral nutrient supply, and water. Even when all these factors are assumed to be constant it is pertinent, in view of the considerable effect of soil texture on the results of aggregate analysis, to question the existence of a critical value applicable to all soils. If a single limiting level holds for both the Drayton and the Hurley soils then the relatively small increase due to the grass ley cannot be of significance in both cases. The elucidation of such problems is the most urgent, and the most difficult, task associated with the evaluation of the grass ley as a factor affecting the physical condition of the soil.

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NITROGEN STUDIES ON THE IRRIGATED SOILS OF THE SUDAN GEZIRA

II. EXTENDED FALLOWING IN COTTON ROTATIONS

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Summary

Seasonal fluctuations in organic nitrogen and nitrate nitrogen in the soil of the Sudan Gezira are described under conditions of extended fallowing in cotton rotations. Statistically, results show that soil organic nitrogen is independent of rotational phase. Cotton yields are not limited by the content of organic nitrogen in the soil, but by soil physical conditions which improve by extended fallowing. Evidence is presented to show that soil organic nitrogen and nitrate nitrogen in this soil do not function in close interdependence. This conclusion was drawn in other work previously published.

In a previous paper (Jones, 1957) the author described the changes in organic-nitrogen content that occurred under three-course rotational cropping in Sudan Gezira soil. The field experiment used for the investigation was one of the long-term rotation experiments at the Gezira Research Farm, Wad Medani, Sudan; but the practical value of the experiment in terms of the general agriculture of the area was limited. Although the frequent cropping involved in a three-course rotation might economically offer a better gross agricultural output than a rotation containing a longer fallow period, it was known that under the intense heat of the Central Sudan fallowing was highly beneficial and permitted of better weed control through cessation of watering. What was not known, however, was the optimum length of fallow.

In order to investigate this point a 'combined-rotations' experiment (Crowther and Cochran, 1942) was laid down, and the present paper describes a study of the changes in soil organic nitrogen and nitrate nitrogen that occur under extended fallowing on this experiment in the Gezira. The experiment was planned to provide a comparison between one-, two-, three-, and four-course rotations in terms of fallows following cotton together with the variations from inclusion of intervening dura (*Sorghum vulgare*) and lubia (*Dolichos lablab*). Ten rotations were involved with a total of thirty phases. The different treatments were completely randomized in each of five blocks making a total of 150 sub-plots. Each sub-plot was $\frac{1}{4}$ feddan* in area.

Data for the dura and lubia variations are not included in the present paper, which is restricted to an examination of soil samples taken from all phases of the following rotations: A, continuous cotton; M, cotton and one year fallow; G, cotton and two years fallow; K, cotton and three years fallow. The five rotation replicates per phase were sampled for

* 1 feddan = 1·038 acres.

top-foot soil in the northern and southern halves of each sub-plot giving ten samples for analysis per phase per sampling date. Sampling was done at regular intervals throughout the year, and this paper presents the results for the seasons 1949–50, 1950–1, and 1951–2. All sampled material was treated as described previously (Jones, 1957) and results are expressed on an oven-dry basis.

Results of Chemical and Statistical Analyses

The cropping season for cotton in the Gezira is considered as beginning in May when the land is cleaned and cultivated in preparation for sowing in August. The season ends in April following the pulling up

TABLE 1

Organic-nitrogen and Nitrate-nitrogen Values (p.p.m.), as Means per Sampling Date, for All Phases of All Rotations

Sampling dates in months	*Season 1949–50*		*1950–1*		*1951–2*	
	Org. N	NO_3-N	*Org.* N	NO_3-N	*Org.* N	NO_3-N
May	226	2	..	..	..	..
June	227	4	234	4	232	3
July	228	3	238	5	236	3
Aug.	229	8	239	2	240	4
Sept. (i)	227	5	238	3	237	4
(ii)			235	2		
Oct.	224	5	232	3	234	5
Nov.	223	3	234	3	233	5
Dec.	226	4	234	2	233	5
Jan.	224	4	231	3	232	4
Feb.	223	4	231	2	230	5
Mar. (i)	215	4	229	2	230	3
(ii)			228	3		
Apr. (i)	225	4	224	2	228	4
(ii)			230	2		
May	225	4	233	3	..	..
Sig. Diff.	4·5	1·1	3·5	0·7	2·2	1·5

and burning of all cotton debris. Seasons subsequently quoted, as for example, 1949–50, involve the period May 1949 to April 1950. Results of the soil organic-nitrogen and nitrate-nitrogen analyses over the seasons 1949–50 to 1951–2 are given in Tables 1 and 2. Analysis of variance has established changes of significance in these figures at $P = 0{\cdot}05$ level.

In general there were no significant differences between rotational phases in either organic nitrogen or nitrate nitrogen. The organic-nitrogen contents of the first and fourth K phases in 1949–50 were significantly lower than other phases; although these two values were also low in succeeding seasons the differences between them and values for the other phases did not again attain significance. The reason for these low values is not understood, but it is known from field observations that some of the constituent sub-plots which contributed to the

means of the first and fourth K phases have suffered loss of level through irrigation and subsequent swelling and drying of the heavy clay soil. This factor will certainly introduce abnormalities into normal performance. The interaction of rotations × dates was not significant.

TABLE 2

Organic-nitrogen and Nitrate-nitrogen Values (p.p.m.) as Means per Rotational Phase over the Whole Season. (Letter and Number within Brackets Refer to the Crop or Year of Fallow.)

Season 1949–50			*1950–1*			*1951–2*		
Phase	*Org.* N	NO_3-N	*Phase*	*Org.* N	NO_3-N	*Phase*	*Org.* N	NO_3-N
A(C)	241	3	A(C)	251	2	A(C)	248	4
M(F)	245	4	M(C)	255	3	M(F)	260	4
M(C)	235	3	M(F)	244	2	M(C)	244	4
G(F2)	222	4	G(C)	237	3	G(F1)	228	4
G(C)	222	4	G(F1)	230	2	G(F2)	219	5
G(F1)	227	4	G(F2)	216	3	G(C)	235	4
K(F1)	201	4	K(F2)	210	3	K(F3)	205	5
K(F2)	233	5	K(F3)	239	4	K(C)	241	4
K(F3)	222	6	K(C)	239	3	K(F1)	242	5
K(C)	198	4	K(F1)	206	2	K(F2)	209	4
Sig. Diff.	25·3	N.S.		N.S.	N.S.		N.S.	N.S.

Significant differences between sampling dates occurred for organic nitrogen and for nitrate nitrogen. The organic-nitrogen content attained a maximum in July–August during the rains, and slowly decreased to a minimum during the dry season of March–April.

Discussion

Organic-nitrogen figures for the 'combined-rotations' show similarities with those for the 'three-course-rotation' experiment (Jones, 1957). Both experimental sites display a marked rainy-season maximum and a dry-season minimum in organic-nitrogen content, although the amplitude of the fluctuation between maximum and minimum values is much less in the 'combined-rotations' than in the 'three-course' experiment. This is due mainly to the lower intrinsic fertility of the site of the former experiment compared with the latter, a fact which has been persistently clear in yield studies over many years.

Organic-nitrogen values are also independent of rotational phase and accordingly of rotation. Taken in conjunction with observations on the 'three-course-rotations' this fact now emerges very positively, irrespective of whether the rotation contains fallow phases or whether it is close cropped. As mentioned earlier, the 'combined-rotations' experiment was intended to investigate the optimum length of fallow in the Gezira, since fallowing was highly beneficial to subsequent cropping. It seems clear, therefore, that neither fallowing nor close rotational cropping induces nutritional benefits on later yields by way of organic nitrogen, and that soil organic nitrogen is not a limiting factor for plant growth.

In view of this, and since plant growth within one season and between rotations is markedly associated with soil-nitrate differences (Tothill, 1948), it is logical to conclude that mineralized nitrogen and organic nitrogen in Gezira soil do not function in close interdependence. This claim was made in a previous publication (Jones, 1957), and the present paper offers further supporting evidence.

Soil nitrates reported here show slight increases during the rainy season, but in general do not display very marked fluctuations. This is in distinct contrast to those figures given previously for the 'three-course-rotations'. Furthermore there are no significant differences between rotational phases. Benefits obtained from fallowing are however clearly seen in the yield figures of Table 3.

TABLE 3

'Combined-rotations' Cotton Yields and Associated Seasonal Means of Nitrate Nitrogen (p.p.m.)

	Season 1949–50		*1950–1*		*1951–2*		*Long-term Means*	
Rotation	NO_3-N	*Yield kpf*•	NO_3-N	*Yield kpf*	NO_3-N	*Yield kpf*	NO_3-N	*Yield kpf*
A	3	1·25	2	1·82	4	0·92	3	1·50
M	3	2·81	3	4·22	4	1·40	4	2·62
G	4	3·15	3	4·79	4	1·96	..	3·48
K	4	3·82	3	6·56	4	2·66	..	4·08

• kpf = kantars per feddan.
1 kantar = 312 lb. of unginned cotton.

Crowther (1943) assumed that these benefits arise from the improved physical condition of the soil through desiccation which should lead to improved nitrifying conditions and hence to a greater degree of nitrification. Jewitt (1945) has shown that Gezira soil is not generally deficient in nitrifying bacteria and that no striking differences exist in this respect between this soil and soils of other arid regions.

The present work supports Crowther's assumption and it appears that the physical condition of the soil is the limiting factor to plant growth in these experiments. Extended fallowing improves the soil structure by exposing the soil to alternate wetting in the rainy season and drying and cracking by extreme insolation in the dry season. These effects are clearly accumulative as shown by the yield increases between none and three years fallowing. There are, however, no attendant increases in soil nitrates as suggested by Crowther, since the maximum possible nitrate accumulation on these plots is a function of the microbiological qualities of the site. The improved physical qualities of the site after fallowing then provide a healthier environment for plant roots and enable the soil nitrates to be more readily absorbed by the roots.

The lack of influence of organic nitrogen on nitrate supply, the cropping potential of a three-course rotation and the presence annually in the dry season of a 'bastard' fallow (Crowther, 1943) in the Gezira

suggest a reforming of the original question put to the 'combined rotations' experiment. It is not the optimum length of fallow that is of real economic importance to the Gezira. Instead is required a form of cultivation during the period of 'bastard' fallow which will induce structural improvement in the soil in three months, equal to the recognized improvement induced by extended fallowing which involves so much empty land for so many years.

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CARBON STUDIES ON THE IRRIGATED SOILS OF THE SUDAN GEZIRA

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Summary

The seasonal variation in the organic-carbon content of Gezira soil under irrigated rotational cropping has been studied over three successive years. Emphasis has been placed on the cotton phases of the rotations. Significant differences in organic carbon occurring between rotations did not produce differences in degrees of nitrogen fixation. It is suggested that fixation and mineralization of nitrogen occur so rapidly in this soil that it is not possible by chemical analysis to determine the amount of nitrogen fixed.

Seasonal changes in organic-carbon content display a phase of slow fluctuation when the soil is wet and carries a crop, and a phase of rapid fluctuation when the soil is bare, dried by insolation, and cracked. Attention is drawn to this phase and to the need for better understanding of the associated phenomena which contribute to the maintenance of high fertility in these arid soils.

As a further contribution to a better understanding of the organic cycle in the arid irrigated soil of the Sudan Gezira, this paper describes a study of the seasonal variations in organic carbon under three-course rotations. Seasonal variations in organic and nitrate nitrogen and the influence of extended fallowing in cotton rotations on these constituents have been previously described (Jones, 1957, 1958).

Experimental and Results

Analysis of organic carbon was undertaken on the identical 'three-course-rotations' samples used in the organic-nitrogen study (Jones, 1958), although carbon analyses were not commenced until the 1949–50 season. The detailed analytical procedure was essentially that of the Walkley-Black method as described by Piper (1942), but modified by Middleton (1951) to suit local conditions. The 'organic-carbon, Walkley-Black values' have been corrected for 75 per cent. recovery although the arbitrary nature of this figure is appreciated. All results are quoted on an oven-dry basis. Analysis of variance was carried out on each season's figures and differences in organic-carbon content were assessed at $P = 0{\cdot}05$ level of significance. Significant differences existed between rotations and between sampling dates. These are shown in Table 1 and Fig. 1. There was no interaction between dates and rotations.

TABLE 1. *'Organic-carbon, Walkley-Black values' in p.p.m. of soil, as rotational means over whole season*

Rotation	*Season*		
	1949–50	*1950–1*	*1951–2*
1. FFC* . .	3,804	3,652	3,797
2. DFC . .	3,980	3,695	3,746
3. DDC . .	4,018	3,796	3,907
4. LFC . .	4,164	3,893	3,989
5. DLC . .	4,091	4,021	3,971
Sig. Diff. . .	89	130	171

* F, fallow; C, cotton; D, dura (*Sorghum vulgare*); L, lubia (*Dolichos lablab*).

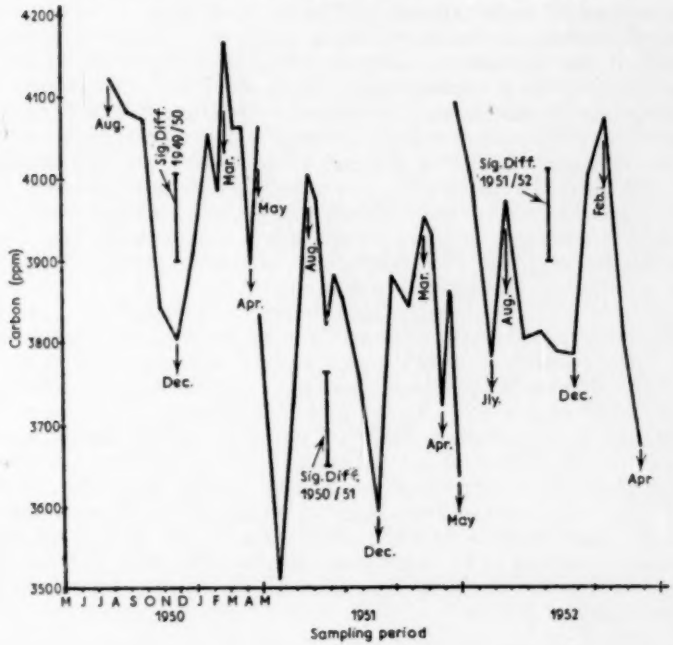


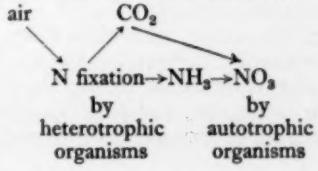
FIG. 1

Discussion

Rotations 4 (CLF) and 5 (CDL) maintain the highest organic-carbon contents while lowest levels are usually associated with rotation 1 (FFC). On the other hand the presence of dura in the rotation tends to encourage higher levels.

When the dura is harvested the stubble is left in the soil and appears to be very resistant to microbiological attack since the root residues can be seen in the soil many months afterwards. These roots help to bind the soil during the 'bastard' fallow (Crowther, 1943) of the dry season but have a detrimental effect on later cropping (Jones, 1957; Conrad, 1928, 1932).

In spite of these differences there were no significant differences in organic-nitrogen content although rotational differences in nitrate nitrogen were established (Jones, 1957). In view of this it seems probable that the microbiological conversions illustrated:



occur so rapidly under Gezira conditions as to make measurement by chemical analysis of the intermediate stage of nitrogen fixation very difficult, if not impossible. Organic nitrogen contents determined by a Kjeldahl analysis therefore depict a fairly stable soil constituent, some ill-defined and relatively small portion of which may still be in the form of readily available microbiological protein. The greater portion of the organic nitrogen will represent nitrogenous forms intimately associated with clay minerals (a fact now readily appreciated), and not easily decomposed by soil bacteria. Birch and Friend (1956) have recently shown that a strongly bound fraction of soil organic matter is released from montmorillonitic clay during the alternate wetting and drying cycles to which it is subjected in nature.

Associated with the strongly bound nitrogen there will be a necessary proportion of organic carbon. In so far however as rotational differences in the latter constituent have been established it is reasonable to assume that these differences ultimately induce the rotational nitrate differences also observed in this soil. Accordingly if we assume a C/N ratio of 10 for the body protein of microbiological forms we can calculate how much nitrogen is differentially fixed between the rotations by heterotrophic bacteria through the agency of the different carbon contents. The net result then is a basic uniform organic nitrogen content over the five rotations which remains relatively stable plus a transient portion resulting from the activity of heterotrophic bacteria. This latter fraction gives rise to differential rotational effects in nitrate by the action of autotrophic bacteria. Thus

	1949–50	*1950–1*	*1951–2*
Highest carbon figure	4,164	4,021	3,989
Lowest carbon figure	3,804	3,652	3,746
Difference	360	369	243
Approximate equivalence as organic N assuming C/N = 10	36	37	24

The final equivalence figures provide a rough guide to the quantity of organic nitrogen in the form of bacterial body protein which was fixed by heterotrophic bacteria and which was available for conversion to nitrate. The figures are approximately 12 per cent. of the organic nitrogen content of the soil as measured by Kjeldahl.

An approximation of the full microbiological contribution to soil organic nitrogen in Gezira soil may be double the figure just given, since even the lowest carbon figure of rotation 1 (FFC) provides some available carbon for consumption by heterotrophic bacteria and since rotation 1 displays a nitrate supply for plant growth comparable with rotation 5 (CDL) (high in organic carbon).

Changes in organic carbon with time (Fig. 1) show a more regular trend than that displayed by organic nitrogen, maximum and minimum values occurring at precise times during the year. The large and prolonged fluctuation occurring between August and February–March covers the greater part of the cropping period for cotton in the Sudan

Gezira. Sowing is started about mid-August and from then until December the cotton plants are actively metabolizing. Proliferation of soil bacteria is intense under the stimulating influence of rain and later irrigation water, and the growing cotton plant is provided with ready nutrient replenishment through its active root. It is to be expected then that the loss of carbon dioxide from the soil arising from bacterial respiration will be mirrored in a drop in soil organic carbon during this time. From December to March the cotton crop is picked, the plant itself becomes increasingly senescent and root hairs slough off and die away. This appreciable contribution to the soil readily explains the increase in carbon content which is observable during this period.

Usually from March to mid-July the high day temperatures coupled with desiccating winds cause the soil to dry and crack. This is enhanced by the routine removal of the dead cotton plants and the following fallow-weeding practice (Crowther, 1943), the actual temperature of the top soil corresponding closely with the maximum temperature in a standard meteorological screen. From these data it would be expected that conditions would prohibit microbiological activity. Fig. 1, however, shows that the February–March maximum in organic carbon content is rapidly lost and a period of fairly rapid fluctuation in carbon content begins continuing until the major peak in August is again established. The rhythmic movement in carbon content clearly passes through a slow phase while the soil is wet and carries a crop into an intensive phase when the crop is removed and the soil is dried out and cracked.

The soil is bare and completely free of weeds during these hot months following removal of the cotton crop. This arises from a fallow-weeding practice already described by Crowther (ibid.). Daytime desiccation will lead to spore formation of promising bacteria. Night atmospheric temperatures may however involve a fall of 50° C. from the day maxima and the lag in soil temperatures at corresponding times establishes a temperature gradient across the upper soil layers. Subsoil moisture under such conditions will then diffuse to the surface as vapour, to be condensed thereby moistening the layers of maximum microbiological activity. Deep cracking of the soil would enhance this movement. Whether such a process would bring sufficient moisture to stimulate activity must still be tested experimentally; equally it is not known whether the limited period when the temperature gradient is operative would be sufficient to reverse bacterial activity from spore forming into proliferating. Under temperate conditions it would seem unlikely that a few hours at fairly low moisture contents would be sufficient. Greene (1932) however claims an environmental adaptability in azotobacter which enables them to respire actively and fix nitrogen at much higher temperatures than their temperate analogues. Possession of this property by the Gezira strain of azotobacter might effectively mean that the period when a temperature gradient exists across the upper soil layers would be most efficiently utilized by the stimulated bacteria.

The temperature and moisture conditions thus associated would lead to loss of carbon dioxide through respiration by bacteria and subsequent diffusion into the atmosphere. Birch and Friend (ibid.) have recently

shown that organic matter released from intimate association with clay minerals by alternate drying and wetting is rapidly decomposed to carbon dioxide by the soil micro-organisms. The net effect in terms of the present study would be a fall in organic carbon content.

Increases in organic carbon which necessarily occur during the course of a complete fluctuation involve absolute increases in carbon. Since on the bare, dry Gezira soil at this time there are no external additions in the form of bulky organic manures the source of carbon must be atmospheric and must be 'fixed' by photosynthesis. The presence of green and blue-green algae in Gezira soil is readily observed on plots during those stages following irrigation when the soil is still quite wet and the clay still possesses a dispersed condition. Confirmation of this observation has also been made microscopically. It is not known whether a slight increase in moisture content in the soil during darkness would be sufficient to stimulate active photosynthesis in the blue-green algae during the very short period of activity between dawn and such time as would involve a return of desiccation conditions.

The increase in frequency of fluctuation in soil carbon content in the dry season compared with the wet season directly points to this period of the year as being one of intense microbiological activity. This is contrary to opinions previously held by many. In temperate climates the period of dormancy in soil is considered to be when it is cold and wet—winter. In arid climates the analogous season is thought to be when the soil is hot and dry. Results quoted here tend to discredit this conception. The hot dry season of arid countries is clearly a period requiring the attentions of microbiologists. The present study indicates that an important addition to knowledge would be the study of the influence of night temperatures and heat-gradients from subsoil to surface in inducing sufficiently moist conditions to favour microbiological activity. Not only is the accumulation of carbon by such a mechanism of great importance in arid soils notably low in organic matter, but the subsequent loss of carbon implies that appropriate conversion back to carbon dioxide is providing energy material for the proliferation of the soil micro-flora.

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A STUDY OF CARBON-NITROGEN RATIOS ON THE IRRIGATED SOILS OF THE SUDAN GEZIRA

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Summary

The seasonal fluctuations and rotational differences in carbon-nitrogen ratios are reported under irrigated rotational cropping in the Sudan Gezira. Statistical analysis shows that there are no rotational differences in carbon-nitrogen ratios.

Seasonal fluctuations in the ratio reflect the cropping period in the rotation and also display marked activity during the period of the year when it is very hot and dry.

STUDIES on organic nitrogen and organic carbon in Gezira soil previously published (Jones, 1957, 1958) have provided data from which carbon-nitrogen ratios have been determined. The seasonal fluctuations and rotational differences in this ratio under three-course rotational cropping in the Sudan Gezira are described herein.

Results

The carbon-nitrogen ratio is defined (Food and Agriculture Organization, 1954) as the weight ratio of organic carbon to total nitrogen. If the latter is taken to mean organic nitrogen plus mineralized nitrogen, then the C/N ratio will not reflect what it so frequently is used to portray, namely the balance between carbon and nitrogen in the soil organic matter—material essentially in organic combination. To use total nitrogen in calculating C/N ratios leads to inclusion in the nitrogen figure of nitrogenous constituents—ammonia and nitrate—the formation of which is governed by and reflected in variations in the calculated ratio.

Generally the mineralized fraction of the nitrogen is of such a small order compared with the organic fraction, that inclusion of both quantities in the total nitrogen figure does not appreciably alter the C/N ratio. When, however, nitrates are high (Griffith, 1957) or when organic-nitrogen contents are low as in Gezira soil, the use of total nitrogen figures in determining C/N ratios can be misleading. In the present work the C/N ratio is taken to be the ratio between soil organic carbon (as determined by Walkley-Black analyses) and soil organic nitrogen (excluding the mineralized portion).

Analysis of variance was carried out on the calculated ratios and differences are quoted in the text at $P = 0{\cdot}05$ level of significance. There were no significant differences between rotations. Rotational means over each season are shown in Table 1.

Significant differences existed between sampling dates. These are shown in Fig. 1. There was no significant rotations $\times$ dates interaction.

Discussion

Rotational differences in soil organic carbon and absence of differences in soil organic nitrogen have been discussed previously (Jones, 1957,

TABLE 1

C/N Ratios as Rotational Means over a Whole Season

Season	1949/50	1950/1	1951/2
Rotation:			
FFC*	14·8	17·7	13·7
DFC	15·3	16·6	13·3
DDC	15·9	16·5	14·0
LFC	16·0	16·2	13·5
DLC	15·9	17·7	14·7
Sig. Diff.	Nil	Nil	Nil

* F = fallow; C = cotton; D = dura (*Sorghum vulgare*); L = lubia (*Dolichos lablab*).

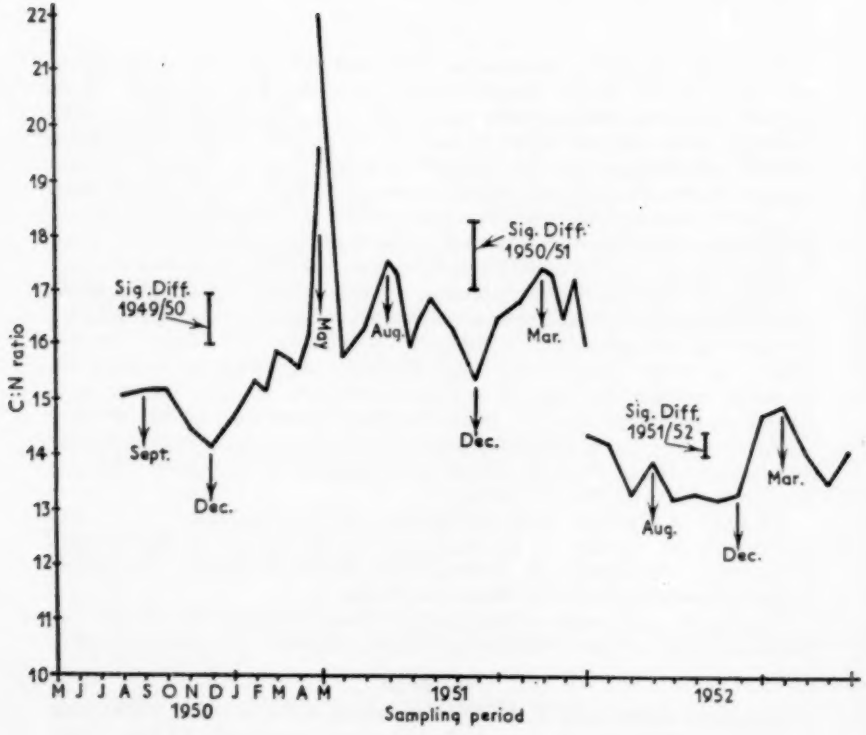

FIG. 1

1958). It was suggested that nitrogen fixed and absorbed into soil organic matter by heterotrophic bacteria was of such transient existence in this soil prior to conversion to mineralized nitrogenous forms, that it was not possible to measure it by means of a Kjeldahl nitrogen determination. It now appears that differences in organic carbon are not great enough to induce rotational differences in C/N ratio; and that these different forms of rotational cropping do not produce differences in the carbon-nitrogen economy of Gezira soil. The general constancy of conditions in the organic fraction adds weight to the suggestion previously made (Jones, 1958) that the soil organic nitrogen measured in a Kjeldahl analysis involves that organic fraction firmly bound to the clay mineral. It is in fact an equilibrium nitrogen value, and should therefore be subject to slight variations between seasons. These variations can be observed in the figures for organic nitrogen, nitrate nitrogen, organic carbon, and in carbon-nitrogen ratios. The between season differences, however, have not been subjected to statistical analysis since there is insufficient data to accommodate this aspect of the problem.

Changes in carbon-nitrogen ratios within seasons and averaged for all five rotations (Fig. 1) bear a close resemblance to the corresponding curves for organic carbon (Jones, 1958). The period of active growth of cotton is reflected in the marked fall in C/N ratio between August and December. From December to March/April the crop becomes increasingly senescent, root hairs slough off, and a general tendency for the C/N ratio to increase is observable.

In May the crop is removed and the soil is left bare and exposed to extreme insolation. During this time until August carbon-nitrogen ratios change rapidly, decreasing generally after March and rising again to a pre-sowing maximum in August. The large increase in April/May 1950 is mainly attributable to a large decrease in organic nitrogen. At a time when the soil is bare and very dry a loss in nitrogen and a corresponding increase in C/N ratio may mean an excess of carbon sufficient to permit some microbiological forms to become active when moisture conditions next become favourable. Supporting evidence for this possibility is offered by the succeeding large fall in C/N ratio during May/June 1950 that is associated with a large increase in organic nitrogen and suggests active nitrogen fixation.

Although still obscure there are indications here of some microbiological forms capable of feeding at extremely low levels of organic carbon, soil moisture, and high temperatures and capable of fixing nitrogen under these exacting conditions.

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FACTORS AFFECTING THE ABILITY OF PLANTS TO ABSORB PHOSPHATE FROM SOILS

III. PLANT-PHYSIOLOGICAL EFFECTS OF IRON

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Summary

In water-culture experiments of short duration the transfer of phosphate to plant shoots is reduced by ferric iron applied prior to or simultaneously with phosphate. The effect is more marked in barley than in rye. The retention of phosphate in roots is similar whether iron is applied simultaneously with or prior to phosphate. Variation in the concentration of phosphate which is supplied to plants has no corresponding effect on the retention of iron in roots. The evidence presented is compatible with the view that phosphate is restrained in roots by ferric ions which have already combined with immobile organic molecules. The atom ratio of iron to phosphate in the resultant complex appears to be 1.

No direct evidence is available to show whether reactions between iron and phosphate *within* plants contribute significantly to the interaction between the two ions which can occur when plants are grown in soils high in labile iron. This possibility cannot however be discounted.

Introduction

THERE is considerable evidence that phosphate in soils can be retained in relatively insoluble forms by its reaction with compounds of iron and aluminium. The 'fixation' of phosphate in acid soils has been attributed to such reactions. Interactions between iron and phosphate can occur also within plants (Biddulph, 1948, 1951; Russell and Martin, 1953). The most consistent effect of iron on phosphate which has already been absorbed appears to be its immobilization in roots, and a consequent reduction of upward translocation. The total phosphate content of plants (i.e. roots plus shoots) bears a more complex relationship to the external concentration of iron. The immobilization of each ion by high concentrations of the other in the shoots of plants has also been reported (Biddulph and Woodbridge, 1952). Both effects attributed to iron, namely the precipitation of phosphate in soil and its immobilization in plants, could result in a low phosphate content in plant shoots. No reference to the physiological aspect has been made in the majority of discussions of the 'availability' of phosphate in soil; it was therefore considered desirable to seek further information on this aspect.

Experimental Methods

Since iron and phosphate are both essential for the growth of plants the effects induced when different levels of the two ions are provided for considerable periods reflect not only the direct effects of each ion on the absorption of the other, but also metabolic differences resulting from the changed nutrient status of the plants. The study of the interaction

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of the ions in the processes of absorption and translocation is therefore greatly simplified by employing short experimental periods, e.g. 24 hours, during which negligible changes in overall metabolism are induced by differences in the quantities of phosphate and iron which are absorbed. Radioactive tracers permit the accurate measurement of absorption in these periods. Such work is of necessity carried out in water culture.

Barley (BN8) and rye (King Two) were used in the experiments. The methods for plant culture, sample preparation and the estimation of P^{32} which were used in the present investigation have been described elsewhere (Martin and Russell, 1950). Iron was deposited onto copper disks by an electro-plating procedure similar to that of Dunn (1951) and the disks were assayed with an end-window G. M. Counter.

The tracer procedure made it possible to confine attention to the quantities of iron and phosphate present in roots and shoots that were absorbed *during the experimental periods*. For the sake of brevity in presentation the terms 'root content' and 'shoot content' are here used to describe only the quantities of the ions absorbed in these periods.

Experimental Results

The effects of iron on the distribution of phosphate within plants

Previous experiments (Russell and Martin, 1953) have indicated that iron absorbed simultaneously with phosphate increases the retention of phosphate in plant roots and thus the quantity transferred to shoots is reduced. This effect was considered to be due to a reaction between iron and phosphate within the root as opposed to on its surface. Since recently absorbed iron is only slowly translocated away from roots it was therefore to be expected that iron would affect the distribution of phosphate in the same manner whether applied simultaneously with it or in a prior period. To investigate this question barley plants at the second-leaf stage, that had been raised in the absence of external sources of iron and phosphate, were treated with 0·001, 0·1, and 10 p.p.m. labelled phosphorus as KH_2PO_4 combined factorially with 0, 0·2, and 2·0 p.p.m. Fe as ferric citrate. The use of the citrate ion minimized the risk of precipitation of iron and phosphate in the external solution. Five replicates of each treatment were employed.

In Fig. 1 the results are shown for an experiment in which iron and phosphate were applied simultaneously for 24 hours. The experiment illustrated in Fig. 2 was similar in design except that iron was applied for 24 hours *prior* to phosphate. Before transfer to the latter solution the plant roots were washed rapidly in water.

In both experiments iron reduced the labelled-phosphate content of shoots and also the transport index (shoot content expressed as a percentage of total plant content) when 10 or 0·1 p.p.m. P were supplied in the external medium. At the lowest phosphate level (0·001 p.p.m. P) very small quantities of phosphate were transferred to the shoots under all circumstances and the content of shoots was reduced by iron only when the highest concentration was applied before treatment with phosphate. The labelled-phosphate content of roots was significantly

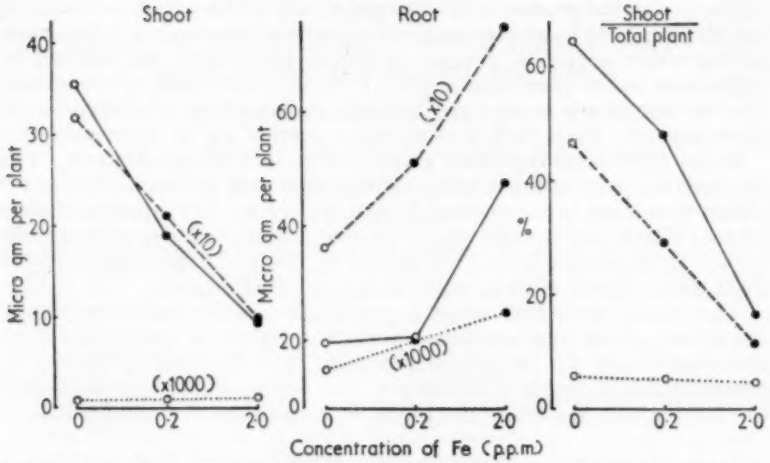

FIG. 1. The effect of iron on the absorption and distribution of phosphate in young barley plants when the ions are supplied simultaneously for 24 hours.

Significant differences cannot be shown as a logarithmic transformation was necessary for statistical analysis. Solid circles are used to denote points significantly different ($P < 0.05$) from the control treatment (0 p.p.m. Fe).

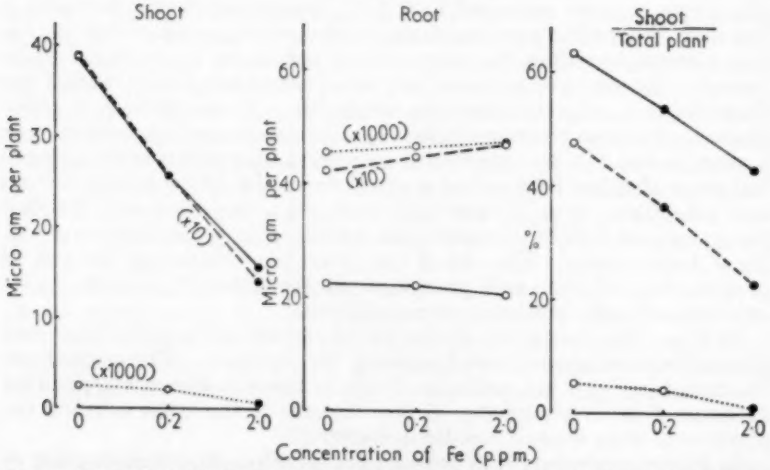

FIG. 2. The effect of iron on the absorption and distribution of phosphate in young barley plants when iron is supplied for 24 hours prior to phosphate. Conventions as in Fig. 1.

increased by iron when both were applied simultaneously; when iron was applied prior to phosphate no significant change in root content occurred. Quantitative differences in the effect of iron thus occurred between the two experiments. However it is apparent that the transfer

of phosphate from roots to shoots was depressed in a generally similar manner irrespective of whether the iron was absorbed prior to or simultaneously with phosphate.

The greater ability of rye than barley to survive in acid soils is well known and evidence has been presented which suggests that labile-phosphate fractions accessible to rye are inaccessible to barley (Russell *et al.*, 1958). Accordingly it was considered of interest to compare the effects of iron on the distribution of phosphate in the two species. Two concentrations of phosphate were applied with and without iron for 24 hours. Both species were affected in a generally similar manner (Table 1). The magnitude of the effect was however markedly greater

TABLE 1

Effect of Ferric Citrate on the Absorption of Phosphate by Young Rye and Barley Plants treated for 24 hours with 2 Levels of Phosphate

	Concentration of Iron (p.p.m. Fe)			
	0		2·0	
Phosphate content of solution (p.p.m. P)	*Rye*	*Barley*	*Rye*	*Barley*
Plant content (mg. P/plant):				
10	1·49	0·97	1·26	0·71
	1·22	*0·98*	*0·12*	*0·84*
	Sig. Diff. (5%) *0·14*			
0·1	0·113	0·086	0·119	0·065
	0·336	*0·293*	*0·345*	*0·255*
	Sig. Diff. (5%) *0·014*			
Transport index (%):				
10	63	79	33	35
0·1	52	45	35	19
	Sig. Diff. (5%) 5			

Values transformed for statistical analysis are shown in italics.

Analyses of Variance

	Statistical significance (P)	
Effect	P *absorption*	*Transport index*
P	< 0·001	< 0·001
Fe	,,	,,
Species	,,	N.S.
P × Fe	N.S.	< 0·001
P × species	< 0·001	,,
Fe × species	< 0·01	,,
P × Fe × species	,,	N.S.

with barley. An analysis of variance showed that the interactions species *versus* iron treatment, and species *versus* phosphate treatment were highly significant with respect to both plant content and the transport index.

Effects of phosphate on the distribution of iron

No adequate interpretation of the interaction of iron and phosphate is possible without information on the effect of phosphate on the distribution of iron. Accordingly, experiments of similar type to those previously described were carried out, but using labelled iron in addition to labelled phosphate.

In Table 2 the results are given for an experiment in which 10·0 and 0·001 p.p.m. P and 0·2 and 2·0 p.p.m. Fe were combined factorially; barley was the test plant and the experimental period was 24 hours. Replication was fivefold.

TABLE 2

The Absorption and Distribution of Phosphate and Iron in Barley Plants when Both Ions were Provided Simultaneously for 24 hours

Initial conc. of culture medium (p.p.m. P)	*Plant content (μg./plant)*		*Transport index*
	Root	*Shoot*	
Phosphate			
10 P, 0·2 Fe	21·1	45·9	65·6
10 P, 2·0 Fe	38·2	28·8	43·0
Sig. Diff. (5%)	3·0	10·9	5·5
0·001 P, 0·2 Fe	0·015 *0·18*	0·0012 *1·08*	7·34
0·001 P, 2·0 Fe	0·038 *0·58*	0·0030 *1·48*	7·40
Sig. Diff. (5%)	*0·20*	*0·33*	
Iron			
Fe 2·0, 0·001 P	44·9 *1·65*	2·65 *1·42*	5·57
Fe 2·0, 10 P	39·7 *1·60*	1·44 *1·16*	3·50
Fe 0·2, 0·001 P	8·50 *0·93*	0·458 *0·66*	5·11
Fe 0·2, 10 P	7·25 *0·86*	0·161 *0·21*	2·17
Sig. Diff. (5%)	*0·10*	*0·11*	1·50

Values transformed for statistical analyses are shown in italics.

The effect of the interaction of iron with phosphate on the quantities of the two ions in roots and shoots was markedly different. Iron again increased the quantity of simultaneously absorbed phosphate found in roots and depressed the phosphate values of shoots when 10 p.p.m. P was provided. The iron content of roots was however not significantly affected by phosphate while the content of shoots was depressed. A further feature of the results was the consistently lower transport indices for iron than for phosphate.

If the retention of phosphate in roots resulted from its combination with iron which was in a free ionic form it would be expected that the addition of phosphate would increase the iron content of roots. Since

this did not occur it seemed possible that the iron which affected the upward movement of phosphate was bound in the roots by a mechanism which would have prevented its transfer to the shoots even if the phosphate was not present. To obtain preliminary information on the form of recently absorbed iron, roots were extracted in a series of buffer solutions of decreasing pH. The following buffer mixtures were employed:

pH 5 and 4	Sodium acetate and acetic acid.
pH 3	Potassium hydrogen phthalate and hydrochloric acid.
pH 2 and 1	Potassium chloride and hydrochloric acid.

The roots of batches of ten barley plants which had been treated for 24 hours with 0·1 p.p.m. P labelled with P^{32} in the presence and absence of 2 p.p.m. Fe were killed in 40 ml. of buffer of pH 5 at 90° C. They were then ground with a pestle and mortar. The resultant suspensions were shaken for 1 hour and then centrifuged. Two such extractions were carried out, and the supernatant solutions were bulked for assay. The procedure was then repeated with the next buffer solution in the series. After treatment with the buffer of lowest pH the residue was digested and assayed. It is apparent from Fig. 3 that the bulk of the phosphate which had been immobilized in roots by iron was not removed until the acidity was increased to pH 1 though the release commenced at pH 4. The phosphate fraction which was extractable at pH 5 was by contrast affected by iron only to a small extent; the same was true for the fraction which was not extractable with pH 1. These two fractions are believed to represent inorganic phosphate and nucleotides respectively.

In Fig. 4 the results are shown for another experiment in which plants were treated with 0 or 10 p.p.m. P combined factorially and 0, 1, and 3 p.p.m. Fe. Both ions were labelled. Only three buffer solutions were used, namely pH 5, 3, and 1 as the previous experiment had shown that the fractions extracted by them were of major interest. The phosphate fraction extracted at pH 1 was again significantly increased ($P < 0{\cdot}001$) by the presence of iron; at pH 3 a small increase occurred ($P < 0{\cdot}005$). In contrast the quantity of iron extracted at each pH was little increased by the presence of phosphate; the effect was significant only in the fraction extracted at pH 1 for roots which had been supplied with 3 p.p.m. Fe.

From these results the following ratios can be calculated in terms of gramme-atoms of iron and phosphate extracted at pH 1.

Ratio: (*a*) The ratio of the *increase* in extractable phosphate induced by iron to the *increase* in extractable iron induced by phosphate.

(*b*) The ratio of the *increase* in extractable phosphate induced by iron to the *total* extractable iron present when phosphate was provided.

The values calculated separately for the two levels of iron are:

External concentration of iron	*Ratio* (*a*)	(*b*)
1 p.p.m. Fe	9·4	1·22
3 p.p.m. Fe	7·7	1·15

Calculation (*a*) would give the ratio of phosphate to iron which would

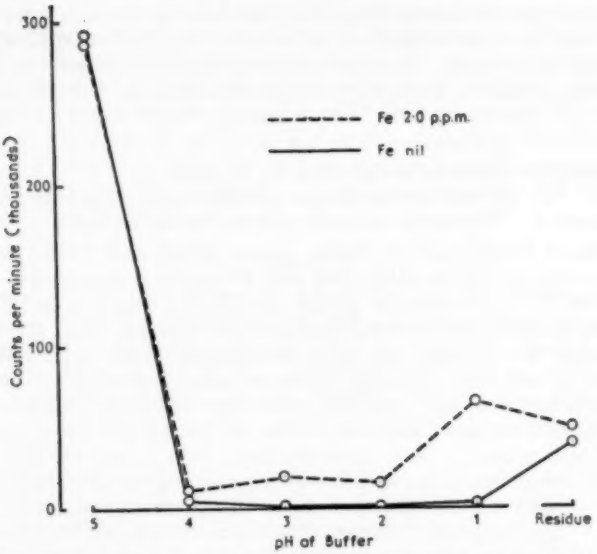

FIG. 3. The extraction of labelled phosphate from the roots of barley plants by buffer solutions of increasing acidity. The plants had been supplied with 0·1 p.p.m. labelled P in the presence and absence of 2·0 p.p.m. Fe.

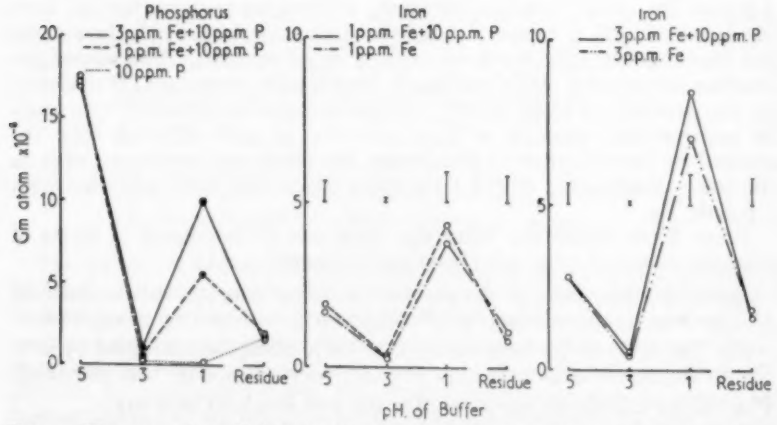

FIG. 4. The extraction of labelled phosphate and iron from the roots of barley plants by buffer solutions of increasing acidity. The plants had been supplied with 0 or 10 p.p.m. labelled P and 0, 1, and 3 p.p.m. labelled Fe combined factorially.

In the left-hand section of the figure significant effects are shown in the same manner as in Fig. 1. Elsewhere significant differences ($P = 0.05$) are shown.

occur in the postulated iron-phosphate complex if the iron and phosphates were both in freely soluble forms before combination. Evidence already presented makes this interpretation unlikely and the high value for the ratio is added evidence against it. The values close to 1 given by ratio (*b*) are compatible with the postulate that phosphate is complexed by iron which is itself already combined with an organic substrate. These results suggest the occurrence of a reaction of the following type:

$$R\,Fe^{+} + H_2PO_4^{-} \rightleftharpoons R\,FeH_2PO_4,$$

where R represents an unidentified organic radical.

It would be simplest to regard the phosphate which participates in this reaction as being present in an inorganic form. Since, however, a major fraction of the phosphate entering plants is rapidly esterified (Loughman and Russell, 1957) the possibility cannot be excluded that labile phosphate esters react with the iron complex.

Discussion

The interactions between ions in the absorption processes of plants may result from several causes. It is well known that ions of similar charge may compete in the initial stages of the absorption process; this may be described as a direct interaction. On the other hand indirect interactions may occur when effects on growth or metabolism induced by alterations in the supply of one ion cause changes in the absorption of others. A further type of indirect interaction is that of iron with phosphate. The present results suggest that this is due to the formation in plant roots of complexes between phosphate and iron which is bound to an organic substrate. The consequent retention of phosphate in roots results in the reduced transfer of phosphate to shoots except when upward transfer is already greatly restricted by virtue of low absorption.

The effect of iron on the upward movement of phosphate appears to be more marked in barley than in rye. Evidence presented elsewhere has been interpreted as indicating that rye has a greater capacity than barley to lower the free energy of phosphate in the initial phase of absorption (Russell *et al.*, 1957). The possibility merits examination that these two effects result from a common cause.

The interaction of iron with phosphate within plant roots has been demonstrated in water culture only. It has not been possible to devise an experimental procedure capable of determining unequivocally whether this effect can be important in controlling the quantity of phosphate which reaches the shoots of plants grown in soils. The difficulty of distinguishing between the direct and the indirect interaction of the two ions is considerable except in experiments of short duration and they are impracticable in soil. A further difficulty in interpreting results obtained in soil arises from the fact that irrespective of the level of iron the transport index for phosphate increases as the quantity of phosphate entering the plant is increased (compare treatments without iron in Figs. 1 and 2). Thus the occurrence of low transport indices in plants grown in acid soils from which the absorption of phosphate is low could not be regarded as evidence of the interaction of iron and phosphate in their

roots. Two facts, however, emerge. First, that when plants are grown in soils which contain a high activity of ferric iron a physiological interaction between iron and phosphate may well occur within the roots. Second, that an interaction of this type would lead to phosphate deficiency in plant shoots. It would seem possible, therefore, that effects attributed to the 'fixation' of phosphate in acid soils may in part be due to this mechanism.

It has been reported that aluminium inhibits the transfer of phosphate to plant shoots (Wright, 1937, 1945, 1953). This question has therefore been investigated by methods similar to those employed in the first two experiments here described (Foster, 1955). No evidence of a direct interaction between phosphate and aluminium was obtained; the reduced translocation of phosphate to plant shoots which can be occasioned by the absorption of aluminium is interpreted as a consequence of the toxic action of that ion in plant roots.

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STUDIES ON THE BASALTIC SOILS OF NORTHERN IRELAND

VI. CATION-EXCHANGE CAPACITIES AND MINERALOGY OF THE FINE-SAND SEPARATES (0·02–0·2 mm.)

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Summary

The fine sand separates (0·02–0·2 mm.) from five basaltic soil profiles have considerable cation-exchange capacities (C.E.C.) ranging from 16·5 to 31·4 m.e. per cent. Only a small part of the C.E.C. is due to clay minerals (diameter $< 2\mu$) cemented into aggregates of fine-sand dimensions by free sesquioxides.

Mineralogical studies of the fractions obtained, after separation by the bromoform technique, show all heavy mineral groups (s.g. $> 2{\cdot}85$) to have a high content of pyroxenes (principally augite) followed by the opaque minerals (mainly magnetite). The heavy groups have small C.E.C., i.e. $< 7{\cdot}5$ m.e. per cent., as expected from the mineralogical composition.

In the light fractions (s.g. $< 2{\cdot}85$) which account for 57–80 per cent. of the total fine-sand separates, quartz predominates in fractions from surface horizons of the profiles. In the lower horizons where quartz is less abundant, greenish-yellow particles (pseudo-aggregates) predominate and comprise over 45 per cent. of the light fractions. Whilst zeolites occur only in negligible amounts and felspars do not represent more than 10 per cent. of the light fractions, yet the C.E.C. of these fractions are considerable, ranging from 41·7 to 72·4 m.e. per cent. Refractive-index measurements and colour indicate that the pseudo-aggregates are mainly chlorites. They must be individual particles, since prolonged reduction failed to cause any further disruption.

The calculated values for the C.E.C. of the pseudo-aggregates range from 90 to 110 m.e. per cent.; the same order of magnitude as that for vermiculite and montmorillonite.

X-ray photographs of the isolated pseudo-aggregates from three fine sands show that the particles are of two types: (*a*) principally vermiculitic under good drainage conditions, (*b*) principally montmorillonitic where the drainage conditions are poor. Chlorites could not be detected, but there was a small amount of kaolinite and some amorphous material.

It is suggested that the pseudo-aggregates are individual particles representing an intermediate stage in the weathering of ferromagnesian rocks to the clay minerals, vermiculite or montmorillonite.

The high C.E.C. of the fine sands are due to (i) a small contribution from clay minerals (diameter $< 2\mu$) present in the fine sands as the result of aggregation and cementation by free sesquioxides, and (ii) a major contribution from the pseudo-aggregates, which have C.E.C. between 90 and 110 m.e. per cent.

IT is now generally accepted that a high level of exchangeable cations in the soil is necessary for maximum plant growth. The site of this exchange is normally attributed to the colloid separate, i.e. the clay-humus complex, but the sand separates, which were formerly regarded as inert, are now acknowledged to play an important part also in the chemical reactivity of the soil.

Detailed studies of the basaltic soils of Northern Ireland (McConaghy and McAleese, 1957) showed the cation-exchange capacities (C.E.C.) of these soils (30–35 m.e. per cent.) to be much higher than of similarly

textured soils derived from other parent materials. In addition to the clay separates ($< 2\mu$) the silt separates were found to contribute appreciably to the C.E.C. of these soils (McAleese and McConaghy, 1957), due to the presence in the silts of 'pseudo-aggregates', which are individual particles of a montmorillonitic or vermiculitic character, depending on the drainage conditions in the profile (McAleese and Mitchell, 1958). Further studies showed the fine sands to have considerable C.E.C. and in some instances the contributions by the fine sand fractions to the total C.E.C. of the soils were greater than those of the corresponding clay separates (McAleese and McConaghy, 1957). The extraordinary high C.E.C. values of the fine sands may be questioned on the grounds that it is impossible to remove completely the fine colloidal clay from the surface of the coarser particles. For this particular group of soils, however, attributing the high C.E.C. of the fine sands to contaminating clay would demand the existence of such large amounts of clay as to make the assumption rather improbable. Therefore it was considered that a knowledge of the mineral composition of the significant amounts of fine sand in these soils would be of the greatest importance in elucidating the source or origin of the high C.E.C. of the sands and would contribute towards a greater understanding of the effects of weathering on the reserve plant-nutrient minerals.

Although the coarse sands (2–0·2 mm.) had also the capacity to exchange cations, the present investigation was limited to the fine sands because of the greater value associated with a knowledge of the mineralogical composition of this particular separate (Marshall, 1940; Jeffries, 1946).

Experimental

Twenty-gramme soil samples from five basaltic soil profiles (as described by McConaghy and McAleese, 1957) were taken for this study. The fine sands were isolated as in the International soda method of mechanical analysis (Robinson, 1933) after the usual pretreatment. Part of each sample was reduced by Jeffries's procedure (1946) to remove the free iron oxides and assist identification. One-gramme samples were then separated into two fractions, (*a*) the heavy-mineral group (s.g. $> 2{\cdot}85$), and (*b*) the light fraction (s.g. $< 2{\cdot}85$), by the heavy-liquid technique using bromoform (Matelski, 1951). The fractions were washed in alcohol, dried and weighed. To aid identification, the magnetic minerals were removed from the heavy-mineral group by means of a strong horse-shoe magnet. Small amounts of the uniformly spread minerals were mounted on microscope slides and counts of the individual minerals made using a petrographical microscope and magnification of 150 power.

The C.E.C. of the sand separates were determined by the neutral N.ammonium-acetate method (Schollenberger and Simon, 1945) and the C.E.C. of the heavy and light fractions by the micro-distillation procedure of Mackenzie (1950). The results are the means of duplicate determinations.

Results and Discussion

In Table 1 the fine-sand separates are shown to have appreciable

C.E.C. ranging from 16·5 to 24·8 m.e. per cent. for separates from surface horizons and from 21·2 to 31·4 m.e. per cent. for the separates from the C or C–G horizons. A small increase in the C.E.C. of the fine sands with depth in the profile is accompanied by a considerable increase in the percentage of fine sand. Hence the contributions to the C.E.C. of the soils by the fine sands represent a high proportion of the total,

TABLE 1

The Effect of Reduction on the Percentages (%) and Cation-exchange Capacities (C.E.C.) of Fine Sands (200–20μ) from Basaltic Soils

Profile		*Drainage*	*Horizon (in.)*	*% fine sand in soil before reduction*	*C.E.C. of fine sand before reduction (m.e. %)*	*% fine sand in soil after reduction*	*C.E.C. of fine sand after reduction (m.e. %)*	*% clay (< 2μ) in sands isolated after reduction*
Carnanee	Z111	Fair to Poor	0–10 A	27·4	16·5	26·0	15·6	5·0
	Z112		10–20 G_1	33·7	18·7	31·4	17·4	6·7
	Z113		20+ G_2	34·4	21·2	30·1	18·5	12·6
Beltoy	Z128		0–8 S	16·8	21·7	15·7	20·6	5·1
	Z129		8–16 A–G	17·8	19·8	15·0	17·7	15·6
	Z130		16+ G_2	20·5	28·7	17·1	24·0	16·7
Ballyno	Z114	Poor to Impeded	0–8 A	17·1	20·4	16·0	19·2	6·3
	Z115		8–16 G_1	16·4	22·8	14·6	20·3	10·9
	Z116		16+ G_2	29·3	23·9	25·2	20·6	14·0
Glynn-Hill	Z124		0–10 A–G	14·6	24·8	13·1	22·2	10·4
	Z125		10–15 A–G	16·6	26·2	15·0	23·7	9·5
	Z126		15–20 G_1	21·6	20·3	18·6	17·5	13·7
	Z127		20+ G_2	23·5	24·5	20·8	21·7	11·4
Rashee I	Z117	Good to Excessive	0–8 S	19·0	24·6	16·9	21·9	11·0
	Z118		8–15 S	23·5	28·9	19·6	24·1	16·6
	Z119		15–30 B_2	35·5	29·5	31·2	25·8	12·5
	Z120		30+ C–G	35·1	31·4	30·3	27·1	13·6

especially in the lower horizons. The highest C.E.C. values are observed for the Rashee I profile, a freely draining profile, in contrast to the C.E.C. of the silt separates which are usually greatest where the drainage is poor.

As the basaltic soils have a high content of free sesquioxides (McAleese, 1954) it was considered desirable to determine whether the C.E.C. of the fine sands might be due to clay particles ($< 2\mu$) cemented into aggregates of fine-sand dimensions by the free sesquioxides. On reduction of the fine sands by Jeffries's method (1946) and subsequent dispersion, substantial amounts of clay ($< 2\mu$) (Table 1) are released. The removal of this clay results in only a slight reduction (0·9–4·7 m.e. per cent.) in the C.E.C. of the fine sands. However, it is doubtful whether the rather small quantities of free sesquioxides released by the sands on reduction (unpublished data) would be sufficient to bind the considerably larger amounts of clay contained in the sands. Free sesquioxides may not be the only binding agents in these sands since it has been shown for the silts (McAleese and Mitchell, 1958) that other binders may be present exerting a strong cementing effect on the basaltic soils in the field condition. It is possible that part of this material of clay dimensions ($< 2\mu$) may be the resultant product of destruction of certain minerals (or mineral) during the reduction procedure. X-ray analysis of the clays removed from the sands by reduction shows kaolinite to be the dominant mineral with smaller amounts of vermiculite and/or montmorillonite and much amorphous material, which may be free SiO_2 but not

sesquioxides. Obviously a part of the C.E.C. of the fine sands is due to contaminating clay but the major contribution is associated with some other mineral (or minerals) remaining in the sands after reduction.

The weighed amounts of the heavy (s.g. $> 2{\cdot}85$) and light (s.g. $< 2{\cdot}85$) minerals of the fine sands are recorded in Table 2. The heavy-mineral group constitutes an appreciable proportion (18·5–28·4 per cent.)

TABLE 2

The Percentages of the Light (s.g. $< 2{\cdot}85$) and Heavy (s.g. $> 2{\cdot}85$) Fractions in the Fine Sand Separates (200–20μ)

Profile		*Drainage*	*Horizon (in.)*	*Weight of fine sand after reduction (g.)*	*Weight of light fraction s.g. $< 2{\cdot}85$ (g.)*	*Light fraction as % of total*	*Weight of heavy fraction s.g. $> 2{\cdot}85$ (g.)*	*Heavy fraction as % of total*
Carnanee	Z111	Fair to Poor	0–10 A	0·950	0·736	73·6	0·214	21·4
	Z112		10–20 G_1	0·933	0·707	70·7	0·226	22·6
	Z113		20+ G_2	0·874	0·755	75·4	0·119	11·9
Beltoy	Z128		0–8 S	0·949	0·751	75·1	0·198	19·8
	Z129		8–16 A–G	0·844	0·694	69·4	0·151	15·0
	Z130		16+ G_2	0·833	0·780	78·1	0·053	5·3
Ballyno	Z114		0–8 A	0·937	0·761	76·1	0·185	18·5
	Z115		8–16 G_1	0·891	0·725	72·5	0·168	16·8
	Z116		16+ G_2	0·860	0·787	78·7	0·073	7·3
Glynn-Hill	Z124	Poor to Impeded	0–10 A–G	0·896	0·626	62·6	0·270	27·0
	Z125		10–15 A–G	0·905	0·643	64·3	0·262	26·2
	Z126		15–20 G_1	0·863	0·764	76·4	0·098	9·8
	Z127		20+ G_2	0·886	0·790	79·0	0·096	9·6
Rashee I	Z117	Good to Excessive	0–8 S	0·890	0·606	60·6	0·284	28·4
	Z118		8–15 S	0·834	0·652	65·2	0·182	18·2
	Z119		15–30 B_2	0·875	0·713	71·3	0·156	15·6
	Z120		30+ C–G	0·864	0·577	57·7	0·286	28·6

of the total fine sand from surface horizons decreasing abruptly with depth, apart from the C–G layer of the Rashee I profile. Corresponding to a decrease in the heavy group, the light fraction increases with depth although in three of the profiles studied there is a fall in the percentage of the light fraction in the second horizon, increasing again for the lower horizons. The data for the Rashee I profile appear to be somewhat exceptional. Here the percentages of the light fraction increase to the B_2 horizon at a depth of 30 in. with an abrupt decrease in the C–G horizon below 30 in. The similar amounts of heavy minerals for the surface and C–G horizons of this profile may be explained as due to present-day weathering of drift laid down on material already subjected to an earlier weathering cycle. No correlations can be observed between the amounts of the heavy and light fractions with changes in the drainage conditions of the profiles. The relatively high yields of heavy minerals is a feature which is often common to somewhat mature soils developed on hard rocks.

The kind and amounts of the minerals present in the heavy and light fractions determined by the approximate method of counting (Matelski and Turk, 1947; Van der Marel, 1949) are given in Table 3. Pyroxenes, mainly augite, predominate in the heavy-mineral group followed by the opaque minerals composed mainly of magnetite with smaller amounts of haematite and to a lesser extent, in the gleyed horizons, limonite. The pyroxene content decreases with depth in all profiles with the exception of the Rashee I where the amounts are relatively similar in all horizons.

TABLE 3

Mineralogical Composition of the Heavy (s.g. > 2·85) and Light (s.g. < 2·85) Fractions of Fine Sand Separates (200–20μ)

Profile		Horizon (in.)	Heavy fraction (s.g. > 2·85)			Light fraction (s.g. < 2·85)					Pseudo-aggregates (%)	Remarks
			Iron ores (%)	Pyroxenes (%)	Zircon (%)	Quartz (%)	Zeolites (%)	Plagioclase (%)	Orthoclase (%)	Heavy minerals (%)		
Carnance	Z111	0–10 A	Magnetite 30–35 Haematite 5–10	65	Trace	80	N	5	—	N	5–10	Pseudo-aggregates either sericite or chloritic with some clay minerals.
	Z112	10–20 G_1	Magnetite 25 Haematite 5	65	—	75–80	N	N	N	—	15–20	
	Z113	20+ G_2	Magnetite 30–40 Haematite, Limonite 5–10	50	Trace	50	N	2–3	—	—	45–48	
Beltoy	Z128	0–8 S	Magnetite 35 Haematite < 1	65	—	60	N	N	—	N	30	
	Z129	8–16 A–G	Magnetite 15 Haematite, Limonite 45	40	Trace	30	1–2	10	—	5–8	50	Sericite and chloritic pseudo-aggregates.
	Z130	16+ G_2	Magnetite 35–40 Haematite 10–15	50	—	20–30	—	10	—	5	60–65	
Ballyno	Z114	0–8 A	Magnetite 25–30	70–75	—	80	N	N	—	—	5–10	Pseudo-aggregates mainly chlorite.
	Z115	8–16 G_1	Magnetite 25–30	70–75	—	60	N	N	—	—	20	
	Z116	16+ G_2	Magnetite 40 Haematite 10	45	Trace	30–35	—	2·3	—	N	50	
Glynn-Hill	Z124	0–10 A–G	Magnetite 25–30 Haematite 5	70–75	—	50	N	N	—	N	30	Pseudo-aggregates composed principally of sericite and chlo·itic minerals.
	Z125	10–15 A–G	Magnetite 30 Limonite, Haematite 10–15	70	—	20–30	2–5	N	2–5	N	50–60	
	Z126	15–20 G_1	Magnetite 40	40–45	—	20–30	—	N	—	—	50–60	
	Z127	20+ G_2	Magnetite 40 Haematite < 1	50	—	20–30	—	N	—	10	50–60	
Rashee I	Z117	0–8 S	Magnetite 25 Haematite < 1	75	—	25	1–2	—	—	—	60	Pseudo-aggregates mainly chloritic with smaller amounts of sericite.
	Z118	8–15 S	Magnetite 15 Haematite 5–10	70	—	20	N	N	—	N	70	
	Z119	15–30 B_1	Magnetite 10–12 Haematite 10–12	75	—	10	N	—	—	N	80–85	
	Z120	030+ C–G	Magnetite 25–30	70–75	—	5–10	N	—	—	N	80–85	

Trace, 1 or 2 grains; N, 1 per cent.; —, absent.

Augite, which is relatively resistant to weathering, is the most abundant heavy mineral in all horizons. Whilst less than 1 per cent. of hornblende and hypersthene is present in surface horizons the amounts increase slightly with depth to about 2 per cent. of either mineral in the lower horizons. Brown basaltic hornblende, which is relatively resistant to weathering, may be present but is possibly obscured by the opaque minerals and augite. The opaque minerals comprise over half the bulk of the heavy-mineral suite in many of the separates, which is not surprising, since iron oxides represent some 10–15 per cent. of the total composition of the basaltic rocks of Northern Ireland (Charlesworth, 1953).

Whilst chemical data show the basaltic soils to have a high titanium content (McAleese, 1954), it is not apparent, from the mineralogy of the fractions studied, with which mineral it is mainly associated. The pyroxenes, ilmenite, leucoxene, and, in some cases, rutile, are present in a few of the fine sands, but the exact distribution of these minerals is somewhat obscure. In the majority of the profiles zircon is absent or present in only trace amounts, i.e. one or two grains, but in the C–G horizon of the Rashee I profile about 1 per cent. of this mineral is found. This accumulation of zircon supports an early deduction that the C–G horizon of the Rashee I profile represents an original surface of a soil which developed from the underlying rock prior to the addition of material which constitutes the upper part of the profile as it appears today. It is possible that some of the other accessory heavy minerals are present but concealed by the iron staining. In general the heavy-mineral assemblage is relatively uniform qualitatively both within and between profiles, which implies uniformity of the parent materials from which the basaltic soils are formed.

The light fraction accounts for 57–80 per cent. of the total fine sands. In surface horizons quartz predominates, as expected from the greater degree of weathering of this horizon, with smaller amounts in the lower horizons. Employing the percentage of quartz as a criterion for the degree of weathering the Carnanee and Ballyno profiles have the greatest maturity, followed by the Beltoy and Glynn-Hill profiles. By comparison, the Rashee I profile is rather immature, which provides further evidence to support the conclusion that this profile represents weathering of drift laid down on pre-existing soil. In the lower horizons over 50 per cent. of the light fraction is composed of what are termed 'pseudo-aggregates', the amounts of which decrease in ascending the profile. The greenish-yellow-coloured pseudo-aggregates under the microscope appear to be composite in character with a flaky nature. Feldspars are absent or present in only small amounts in surface horizons, increasing with depth to the lower horizons where they constitute less than 10 per cent. of the total light separate. Plagioclase feldspars are present in all the profiles, but orthoclase feldspar is much less common, occurring in only two of the profiles and in very small amounts. This is as anticipated on account of the low potassium content of these soils. The zeolitic content is generally rather small (less than 1 per cent.) and in only one separate (Z125) accounts for more than 2 per cent. of the total light fraction. Small

amounts of the heavy minerals occur as contaminants in some of the light fractions.

In Table 4 (*a*) results are given of the C.E.C. of the separated heavy and light fractions from the three fine sands Z113, Z116, and Z119. As expected from mineralogical considerations the C.E.C. of all three heavy fractions are small, i.e. $< 7{\cdot}5$ m.e. per cent. However, the C.E.C.

TABLE 4 (*a*)

The Cation-exchange Capacities of the Heavy (s.g. $> 2{\cdot}85$) and Light (s.g. $< 2{\cdot}85$) Fractions of the Fine Sand Separates from Basaltic Soils

Profile	*Horizon no.*	*Depth (in.)*	*C.E.C. of heavy fraction (m.e. %)*	*C.E.C. of light fraction (m.e. %)*
Carnance	Z 113	20+	4·4	41·7
Ballyno	Z 116	16+	5·2	55·2
Rashee I	Z 119	15–30	7·4	72·4

TABLE 4 (*b*)

The Calculated Cation-exchange Capacity of Pseudo-aggregates

Horizon no.	*Pseudo-aggregates in light fraction (%)*	*C.E.C. of light fraction (m.e. %)*	*Calculated C.E.C. of pseudo-aggregates (m.e. %)*
Z 113	45	41·7	91·6
Z 116	50	55·2	110·4
Z 119	80	72·4	90·5

of the corresponding light fractions are found to be very considerable indeed, ranging from 41·7 to 72·4 m.e. per cent. Quartz or feldspars are obviously not the site of all this exchange, although partial weathering of the surface of the feldspars may have given them a small C.E.C. Zeolites are known to have a high C.E.C., but the small amounts present in the light fraction are insufficient to have any appreciable significance. The only other major component of the light fraction is the pseudo-aggregates which are therefore assumed to be the main contributors to the C.E.C. Based on this assumption and from the estimated amounts of the pseudo-aggregates present, calculated values for the C.E.C. of the pseudo-aggregates are given. These values (Table 4 (*b*)) are remarkably high, ranging from 90 to 110 m.e. per cent., which is of the same order of magnitude as found for clay minerals of the montmorillonite or vermiculite groups.

Using the microscope, some of the pseudo-aggregates were isolated by hand picking for further study, and sufficient material was obtained from the light fractions of the three fine sands Z113, Z116, and Z119 to provide specimens for X-ray analysis, but not for C.E.C. determinations.

Examination of the X-ray photographs (obtained by using a Phillips precision camera of 114·83 mm. diameter and preferentially orientated

specimens by the pressure aggregate technique of Mitchell, 1953) showed a faint line at 7·2 kX and a very weak black band around the exit hole of the film in the region 14kX–18kX. In addition, the photographs of glycerol-treated specimens from Z113 and Z119 gave typical vermiculite patterns having a fairly intense 14kX line. Chlorites appeared to be absent as shown by the usually accepted distinction, i.e. thermal stability. However the photograph of the glycerol-treated specimen of Z116 showed clearly the prominent 17·7kX line of montmorillonite.

In the Rashee I profile, where the drainage is described as 'good to excessive', the pseudo-aggregates show the prominent 14kX line of vermiculite. However, for the 'fair to poorly' drained Carnanee profile, the 14kX line is present, but the intensity of this line is not so pronounced as that for the material from the Rashee I profile. This implies that the pseudo-aggregates from the well-drained profile are more vermiculitic in character. After 16 hours exposure a photograph of the pseudo-aggregates from the Carnanee profile shows what appears to be a weak montmorillonitic 17·7kX line, but unfortunately positive identification is somewhat obscured by the black band around the exit hole in the film.

However, photographs of the pseudo-aggregates from the poorly drained Ballyno profile show that they are montmorillonitic in composition. Apparently the composition of the pseudo-aggregates is somewhat dependent on the drainage conditions of the soil. Earlier studies (McAleese and Mitchell, 1958) on the mineralogical composition of the clay separates from these soils have shown that vermiculite occurs under good drainage conditions, but is replaced by montmorillonite where the drainage is poor. These results support the deduction that the pseudo-aggregates represent an intermediate stage in the weathering of ferromagnesian minerals to clay minerals; either vermiculitic under good drainage conditions or montmorillonitic where the drainage is poor.

The reason for the black band around the exit hole of the photographs remains obscure. It is not due to the camera alignment or specimen support as shown by its absence from other photographs. A possible explanation is the occurrence of amorphous material (of unknown composition but possibly SiO_2) associated with the pseudo-aggregates.

Hosking *et al.* (1957) claim that the high contents of clay minerals which they found in the sand fractions of basaltic soils in Australia were due to aggregation and cementation by free sesquioxides. Whilst some clay minerals occur in the sand fractions of the basaltic soils of Northern Ireland as the result of aggregation and cementation by free sesquioxides, by far the greater proportion is not of this composition but present as pseudo-aggregates which must be individual particles of sand size dimensions, since prolonged reduction failed to disrupt these so-called aggregates. The pseudo-aggregates of the fine sands are similar in composition to those occurring in much smaller amounts in the silts. The results of this study show the pseudo-aggregates to be individual particles representing an intermediate stage in the weathering of ferromagnesian minerals either to vermiculite under good drainage conditions or to montmorillonite where the drainage is poor. Their presence in the fine sands is probably the result of the greater degree of chemical

weathering in contrast to mechanical disintegration, giving them a composite appearance and flaky nature. The particles have a high C.E.C. and are the seat of the C.E.C. of the fine sands.

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CHANGES IN THE SOIL OF A LONG-CONTINUED FIELD EXPERIMENT AT SAXMUNDHAM, SUFFOLK

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Summary

A four-course rotation experiment was carried out on wheat, mangolds, barley, and legumes. Yields of all crops were much increased by phosphate fertilizers, nitrogen fertilizers increased yields of non-legumes, extra yields from potash fertilizers were smaller. Fifty-six years of continuous manuring caused the following changes in the calcareous boulder clay soil: Plots receiving farmyard manure contained half as much again organic carbon as plots receiving fertilizers, plots receiving N and P fertilizers contained slightly more organic matter than plots without these fertilizers. Total soil nitrogen was considerably increased by farmyard manure and was slightly higher on plots receiving sodium nitrate than on plots without nitrogen fertilizer. Total soil phosphorus was built up by farmyard manure and by bone meal, and to a smaller extent by light annual dressings of superphosphate. 'Soluble phosphorus' determined by three methods differentiated clearly between plots which had received phosphate fertilizers and those which had received none. An accumulation of bone meal residues was demonstrated by dilute hydrochloric-acid extraction, but not by methods involving extraction with 0·5 M sodium bicarbonate or equilibrium with 0·01 M calcium chloride. Soluble-phosphorus values by all three methods indicated the presence of fertilizer residues more clearly than did values for total soil phosphorus. The soil contained a large quantity of total potassium and the values were not materially affected by manuring. Dilute-HCl-soluble-K and exchangeable-K values differentiated between plots which had received potash fertilizers and those which had received none. They also reflected changes in soluble potassium caused by the different amounts of potassium removed in the crops grown.

Introduction

In Britain records of changes in the soils of long-continued arable field experiments, where cropping and manuring have been controlled for many years, are confined mainly to the Rothamsted and Woburn Farms. To assist in planning the maintenance of soil fertility much more information on the gains and losses of plant nutrients and of organic matter in relation to manuring, cropping, and climates is needed for land in other districts. The opportunity was taken in spring 1957 to sample the soils of the long-term Rotation-I Experiment at Saxmundham in Suffolk and the results are described here briefly. The soils will be used in pot experiments to attempt to measure the value of the nutrients which have accumulated under known manurial treatments.

Description of the Field Experiment and Soil

Agricultural details of the experiment have been given by Oldershaw (1941). It was started in 1899 by the East Suffolk County Council. The rotation practised for the whole period has been:

1, wheat; 2, roots (mangolds were generally grown but swedes or

turnips were taken in five years and the land was fallowed in one year); 3, barley; 4, legume (beans or red clover).

Each crop is present on one block of the experiment in each year. The manurial treatments, which have remained unchanged since the beginning of the experiment, have been applied annually to the same plots in each of the four blocks; they are listed in Table 1.

TABLE 1

Experimental Treatments in Rotation-I Experiment at Saxmundham

Plot no.	*Symbol*	*Treatment per acre*	*Plant nutrients applied annually (approximate estimates)*		
			N	P	K
			(*lb./acre*)		
1	F.Y.M.	6 tons farmyard manure	80	18	70
2	B.M.	4 cwt. bone meal	16	43	..
3	N	2 cwt. nitrate of soda	35	..	..
4	P	2 cwt. superphosphate	..	16	..
5	K	1 cwt. muriate of potash	..	..	47
6	O	No manure	..	..	..
7	PK	2 cwt. superphosphate + 1 cwt. muriate of potash	..	16	47
8	NK	2 cwt. nitrate of soda + 1 cwt. muriate of potash	35	..	47
9	NP	2 cwt. nitrate of soda + 2 cwt. superphosphate	35	16	..
10	NPK	2 cwt. nitrate of soda + 2 cwt. superphosphate + 1 cwt. muriate of potash	35	16	47

The treatments are perhaps unique among long-term experiments surviving from the 'classical' period in having the full factorial arrangement of N, P, and K; the treatments are, however, not randomized but are repeated in each block in the same systematic arrangement. Boyd (1940) has made a full examination of the data accumulated during the first forty years of the experiment with special reference to the effect of seasons on crop yields. No analyses of the crops grown on the experiment appear to have been made at any time in its history.

The soil is a poor calcareous clay loam and is developed from a heavy Chalky Boulder Clay. It now consists of an 8-in. ploughed layer of dark grey clay loam containing a few flint pebbles lying on greyish-brown subsoil which overlies a mottled bluish-grey calcareous clay. Mechanical analyses (given on the basis of oven-dry soil) of samples taken in 1957 are listed below; they show the range of values obtained from the four blocks of the experiment.

	%
Coarse sand	28–34
Fine sand	28–29
Silt	10–11
Clay	22–26

Average crop yields for the whole period of the experiment are given in Table 2; they have been low except where phosphates have been applied. Nitrogen fertilizer has given large increases in yields of all crops except the legumes; potash fertilizers have had smaller effects on yields, even with the crops in the rotation that are sensitive to potassium deficiency (mangolds and legumes).

TABLE 2

Mean Yields per Acre in the Rotation-I Experiment at Saxmundham, 1901–56

Plot no.	1	2	3	4	5	6	7	8	9	10
Symbol	F.Y.M.	B.M.	N	P	K	O	PK	NK	NP	NPK
Wheat grain (bu.)	33·4	25·4	23·8	24·3	17·9	18·2	26·2	26·2	33·2	34·0
Wheat straw (cwt.)	40·2	27·9	29·8	25·8	20·8	20·9	27·9	31·2	36·9	39·3
Mangolds roots (tons)	18·6	11·8	4·6	11·7	4·1	4·3	12·6	5·7	18·1	18·8
Barley grain (bu.)	32·8	22·2	22·1	20·7	16·4	16·6	23·3	24·8	34·1	35·5
Barley straw (cwt.)	29·0	20·2	22·5	17·8	15·8	15·5	20·1	23·3	28·3	29·6
Beans grain (bu.)	39·8	28·6	21·1	31·4	21·4	20·0	36·7	22·0	29·8	37·2
Beans straw (cwt.)	35·9	25·0	17·6	24·4	16·6	15·8	30·0	20·0	26·8	31·6
Clover hay (cwt.)	77·7	55·2	30·6	57·6	34·2	33·4	65·4	37·6	55·0	60·2

NOTE: Means for wheat (straw and grain), mangolds, and barley (straw and grain) are averages over the whole period 1901–56. For beans (straw and grain) and clover hay, the averages are the arithmetic means of the mean yields in the two periods 1901–37 and 1938–56.

Experimental

The soil of each plot was sampled in March 1957 to ploughing depth (0–8 in.). After air-drying and grinding to pass a 2-mm. sieve the samples were analysed to determine the following quantities:

1. Calcium carbonate (using Collins's (1906) method).
2. Organic carbon by the method of Walkley and Black (1934), values are given as determined.
3. Total nitrogen (Kjeldahl method).
4. Total phosphorus (after digestion with perchloric acid).
5. 'Soluble' phosphorus was determined by three methods:
   (*a*) A Rothamsted method using 0·3 N hydrochloric acid, a soil:solvent ratio of 4:10, and shaking for 1 min.
   (*b*) Phosphorus extracted by 0·5 M sodium bicarbonate (Olsen *et al.*, 1954).
   (*c*) Phosphorus in equilibrium with 0·01 M calcium-chloride solution (Schofield, 1955).
6. Total potassium (after treatment with hydrofluoric acid).
7. 'Soluble' potassium was determined in two ways:
   (*a*) Potassium dissolved by 0·3 N hydrochloric acid after shaking for 1 minute at a soil:solvent ratio of 4:10.
   (*b*) Exchangeable potassium determined by the semi-micro procedure of Metson (1956).

These data are presented in Table 3 after averaging values for the four plots in the separate blocks; the variations between the replicate plots of each treatment were small for all analyses.

TABLE 3

Analyses of the Soils of the Saxmundham Experiment

(*Values are averages for 4 plots*)

Plot number	1	2	3	4	5	6	7	8	9	10
Treatment	F.Y.M.	C.M.	N	P	K	O	PK	NK	NP	NPK
$CaCO_3$ %	0·72	0·74	0·76	0·74	0·88	0·83	0·91	0·89	0·82	1·01
Organic carbon % (Walkley and Black values)	1·55	1·01	0·92	0·99	0·95	0·94	1·01	0·95	1·04	1·01
Total N %	0·199	0·149	0·136	0·139	0·137	0·135	0·142	0·139	0·146	0·144
Total P %	0·071	0·088	0·042	0·056	0·041	0·042	0·056	0·041	0·056	0·056
Total K %	1·27	1·18	1·23	1·25	1·30	1·24	1·28	1·27	1·22	1·26
Soluble phosphorus										
(*a*) HCl-soluble } mg. P/100 g.	18·1	28·7	3·4	7·4	2·6	2·0	6·9	3·2	7·3	6·3
(*b*) Olsen method } of soil	3·3	0·8	0·3	2·3	0·2	0·2	2·0	0·2	2·1	1·9
(*c*) Conc. of $P \times 10^{-6}$ M in equilibrium with 0·01 M $CaCl_2$	6·3	0·2	0·1	1·6	0·1	0·1	1·1	0·1	1·4	1·0
Soluble potassium										
(*a*) HCl-soluble } mg. K/100 g.	16·3	5·8	6·5	5·9	14·4	7·2	10·4	13·0	5·7	9·1
(*b*) Exchangeable } of soil	26·8	10·9	12·4	11·6	23·5	13·7	18·0	20·5	11·0	15·4

Results and Discussion

Approximate values for the amounts of N, P, and K added annually by fertilizers between 1901 and 1956 are given in Table 1. Analyses of the farmyard manure applied were not recorded, but Oldershaw (1941) states that it has been of 'average quality'. No use has been made of the estimates of the plant nutrients applied to the farmyard-manure plot and given in Table 1, since these are based on an average analysis assumed for the manure. As no crop samples have been taken from this experiment for chemical analysis it is impossible to construct a factual balance sheet for the amounts of nutrients removed in crops carted off during the last fifty-six years. Average values for the amounts of phosphorus

TABLE 4

Estimates of Gains and Losses of Soil Phosphorus and Potassium in Fifty-six Years of Cropping and Manuring of the Saxmundham Rotation-I Experiment

Treatment	*Estimated gains (+) or losses (−) of*	
	P	K
	lb./acre	
F.Y.M.	(+320)*	(−800)*
B.M.	+1,900	−3,200
N	−350	−2,200
P	+420	−3,100
K	−300	+800
O	−300	−1,800
PK	+380	−900
NK	−400	+300
NP	+280	−4,400
NPK	+220	−1,900

*Since an average composition for farmyard manure has been assumed, these values are very uncertain.

and potassium in crops given by Beeson (1941), together with the average yields which are given in Table 2, have been used to estimate the possible gains and losses in phosphorus and potassium over the period; these data are given in Table 4. (In making these calculations it is assumed that mangold tops have always been ploughed in and that all other produce has been removed.)

Calcium-carbonate reserves are present on all plots, but variations from plot to plot are not associated regularly with treatments.

Organic carbon was built up markedly only on the farmyard-manure plot which now contains one-and-a-half times as much carbon as the plots receiving inorganic fertilizers. Of the plots receiving fertilizers, those having both nitrogen and phosphorus contain slightly more organic matter than those which have received no nitrogen or phosphorus. This is probably due to the greater residues left in the soil by the heavier crops grown on plots receiving N and P manuring.

Total nitrogen in the soil is lowest on the plots receiving no fertilizer

and where only one nutrient has been applied; values on plots receiving NP and NPK fertilizers and bone meal (which contains 3–4 per cent. N) are slightly higher. Farmyard manure gives a much higher value. Boyd (1940) states that the soil contained 0·178 per cent. N at the beginning of the experiment. If the sample used in this early analysis was truly representative, the soil must have lost nitrogen in the following fifty-six years under all except the farmyard manure treatments. Oldershaw (1941) mentions that before starting the experiment the land was drained. Drainage, perhaps associated with the introduction of more frequent intertilled crops and better and deeper cultivations when the land became an experimental station, may have accentuated the rate of decomposition of soil organic matter in the early years of the experiment and led to this lower percentage of nitrogen which is, however, still higher than the value (0·10 per cent. N) on the unmanured plots of the Classical Experiments at Rothamsted (Warren, 1956).

Total phosphorus in the soils of all plots which have received no phosphate manuring was remarkably uniform (0·041–0·042 per cent. P). All plots which had received superphosphate contained rather more phosphorus (*c.* 0·056 per cent. P). Both bone meal and farmyard manure have provided considerable reserves of total soil phosphorus—on bone-meal-treated plots the value is double that on plots receiving no phosphate. Estimates of the possible gains and losses of phosphorus in Table 4 show that the treatments divide themselves into a group which have received phosphate manuring and where phosphorus may be expected to accumulate in the soil, and a second group which have received no phosphate manuring and where soil phosphorus has been lost. Data for total soil phosphorus in Table 3 support these estimates.

Soluble phosphorus determined by the three methods also differentiates clearly the plots that receive farmyard manure, bone meal, or superphosphate from those receiving no phosphate. The rapid Rothamsted test (using dilute HCl) gives the highest values on the plots that receive bone meal, about one-third of the total soil phosphorus being soluble in the reagent. The plots treated with farmyard manure also contained much HCl-soluble phosphorus. Plots receiving superphosphate contained about twice as much HCl-soluble phosphorus as the plots receiving no phosphate fertilizer. Values for both 0·5 M bicarbonate-soluble phosphorus and the equilibrium concentration of phosphate in 0·01 M calcium chloride fall in the same order: D > P > NP > PK > NPK > BM > N = K = O = NK. The plots having bone meal produce about the same yields of wheat, mangolds, and barley as the plot receiving superphosphate (Table 2), but both the above methods of soil analysis indicate that soluble phosphorus on the bone-meal-treated plot is much less than on the superphosphate plots. The values obtained by extraction of the soil of the bone-meal-treated plots with bicarbonate and with calcium chloride are both so low that, based on experience of similar calcareous soils at Rothamsted, a response to superphosphate would be expected. It is, however, difficult to interpret the behaviour of bone meal for non-legumes since the dressings used have supplied about 16 lb. nitrogen each year as well as phosphate. The

amounts of phosphorus extracted by hydrochloric acid appear to be anomalously high, which is to be expected, as bone phosphates are soluble in this acid. Warren (1956) showed that the rapid test used here was unreliable on calcareous Rothamsted soils containing residues of rock phosphate, but that there was good agreement between bicarbonate-soluble phosphorus and crop yields.

Soluble-phosphorus values determined by bicarbonate extraction and by equilibrium measurements in 0·01 M calcium chloride also agree qualitatively with differences in the estimated amounts of phosphorus

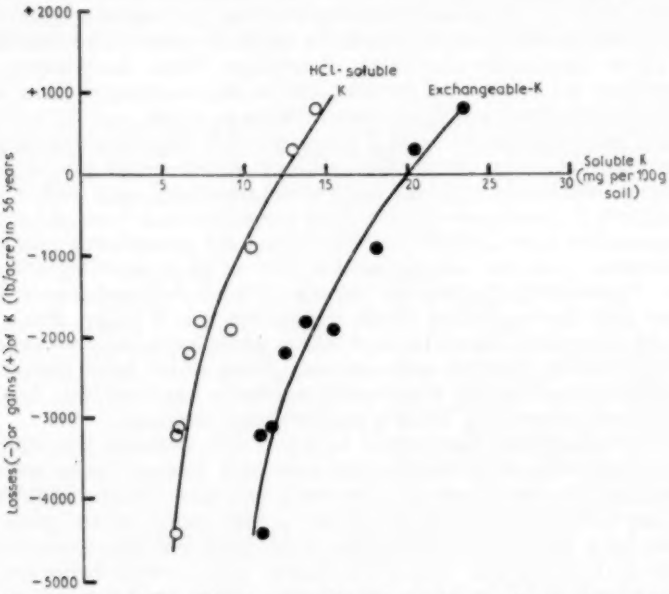

FIG. 1. The relationships between the gains or losses of potassium estimated to have occurred during 56 years at Saxmundham and the amounts of HCl-soluble K and exchangeable-soluble K in the soils.

removed as a result of the differential nitrogen and potassium manuring of the superphosphate-treated plots. Both methods give the lowest values (Table 3) on the plot receiving NPK manuring; the highest values were obtained where superphosphate only was applied. On this plot the net gain of soil phosphorus has been greatest (Table 4), since crop yields have been lower.

Total-potassium values are relatively uniform for the various treatments. In view of the large reserves of potassium present (about 25,000 lb./acre in the surface layer) it is not surprising that the effects of removal by crops or of potassium manuring are not clearly defined.

Soluble potassium determined by both methods differentiated clearly between plots treated with muriate of potash or with farmyard manure

and plots which have received no potash fertilizers. Estimates, made in Table 4, of changes in soil potassium suggest that muriate of potash did not supply sufficient potassium to balance that removed by crops except where the lack of nitrogen and phosphate manuring so restricted crop yields that potash manuring was more than sufficient to balance the potassium removed by the crops (i.e. treatments K and NK). The various combinations of K manuring with N and P manuring that affected crop yields and, presumably, potassium uptakes provide a wide range of values for the estimates of the amounts of potassium lost in the fifty-six years. Fig. 1 shows that there is a clear relationship between the values for 'soluble' potassium by two methods and the estimated losses or gains of soil potassium given in Table 4. Both methods of analysis are successful, but values for exchangeable K appear rather more satisfactory than values for HCl-soluble K. It is interesting that on some plots which have received only N and P manuring soluble potassium has now reached a deficiency level. If the general level of manuring with nitrogen and phosphate were to be increased in this experiment it is possible that those plots which have received no potash for fifty-six years would no longer be able to supply sufficient potassium for the bigger crops grown and that much more marked responses to potash fertilizers would be obtained. The general level of yields during the 1901–56 period was not high for the district and there is little doubt that much larger crops would be obtained by using higher levels of nitrogen manuring.

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WATER UPTAKE BY PURE CLAYS AND SOIL CRUMBS*

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Summary

Wetting experiments on pure clays are described that lead to the conclusions that entrapped air is neither a necessary nor an important factor in slaking of dry soils, and that slaking is always associated with rapid intercrystalline swelling of the clay. If swelling is suppressed, or takes place slowly—as from a vapour phase—slaking does not occur, and it is suggested that slow swelling gives time for re-adjustment of the internal geometry of the clay, so producing some dislocation but no disruption. In N NaCl, a Na-montmorillonite swells to about twice its dry thickness, and in an atmosphere of 98 per cent. relative humidity it gains about one-third of its weight. Both these figures are in agreement with the usual estimate of surface area of 800 $m.^2/g$. Under the same conditions a Na-illite (from Willalooka) swells by about a third of its dry thickness, and gains about a quarter of its dry weight.

Studies on rates of uptake of water vapour indicate that montmorillonite has taken up less than a quarter of its equilibrium water content at 98 per cent. relative humidity within 10 min., whereas illite has taken up one-third of its water in the same time, the clays then being stable against subsequent flooding.

In the field it is probable that water vapour diffuses ahead of a liquid wetting front, and the protective effect of the resultant slower pre-swelling of the clay prevents the slaking action of rain from affecting more than a thin surface layer of soil.

1. *Introduction*

Two main mechanisms have been suggested for the breakdown of dry soil crumbs on wetting (slaking). An explosive air pressure could be produced by sudden release of air adsorbed on clay (Sobolev and Chapek, 1930), or sudden compression of entrapped air (Yoder, 1936; Russell, 1938; Hénin, 1938; Robinson and Page, 1950; Mazurak, 1950; Emerson and Grundy, 1954). Alternatively, or simultaneously, disruptive mechanical forces could be set up by rapid swelling of clay in the soil. There is some confusion about the conditions in which these mechanisms operate. Suppressing the swelling by wetting with alcohol or non-polar liquids reduces the slaking (Hénin, Robichet, and Jongerius, 1955). Wetting in a vacuum largely reduces the slaking but leaves a residual action attributed to swelling (Russell, 1938), but the humidity in the 'vacuum' appears to be very important. Russell and Tamhane (1940), and Smith and Browning (1946) found that there was no slaking if the soil air was first replaced by water vapour, and Panabokke and Quirk (1957) made these observations more quantitative by establishing that aggregates remained stable if slowly pre-wetted to a pF wetter than pF 2 (99·3 per cent. relative humidity), and that the aggregates did not break down beyond 0·25 mm. until the pF exceeded 4·7 (96·4 per cent. relative humidity). In a detailed study of the swelling factor, Brewer and

* This work forms part of a thesis approved for the M.Sc. degree of the University of London.

Blackmore (1956) showed that where there was optical evidence of considerable regular orientation of the clay, there was rapid slaking on wetting, but with random orientation slaking was less severe and might be attributed to the effect of entrapped air.

In the experiments now to be described an attempt has been made to remove some of the inconsistencies in existing evidence, and, in order to give swelling phenomena maximum chance of operation, much of the work has been done on pure clays.

2. *Experimental Material*

Pure clays

Montmorillonite—Dakota Bentonite 'Volclay' supplied by American Colloid Co.

Illite—the separated clay fraction of Willalooka subsoil supplied by C.S.I.R.O., Australia. X-ray analysis indicates that the $< 2\mu$ fraction is 85 per cent. illite and 15 per cent. kaolin. Although the fine fraction of this material satisfies most of the definitions of an illite, it will be seen that it swells in water. A chemical analysis is given in the appendix.

Kaolinite—'colloidal kaolin' supplied by Merck and Co. No mica or montmorillonite present.

Grundite—an illite from Goose Lake, Illinois, U.S.A., supplied by Illinois Clay Products Co. The 1μ fraction is 75 per cent. vermiculite and 25 per cent. mica.

Soils and soil clays

Barnfield—a calcareous clay soil from a Rothamsted field that has been under continuous arable cultivation for 80 years. The samples have been taken from the plot that has had no manure or fertilizer in that period, and has the poorest structure of any soil within easy reach. The clay minerals present are predominantly mica types (60 per cent.), kaolinite (40 per cent.), and a little vermiculite.

Willalooka subsoil—a calcareous subsoil from South Australia. The clay fraction is mostly fine illite, and some kaolinite.

Weston Turville surface soil—a montmorillonitic soil from near Aylesbury, Bucks., which has been under continuous arable cultivation.

Gault clay—a montmorillonitic subsoil obtained from the Cambridge University Farm.

Preparation of the clays

After treatment with 40 volume H_2O_2 the 1μ fraction was separated by sedimentation, flocculated with N NaCl, and then centrifuged and decanted from N NaCl+0·001 N HCl several times to sodium saturate the clay and displace any exchangeable Al^{+++}. The illite, grundite, and montmorillonite were brought into suspension and dialysed in cellulose casings against distilled water in which the pH was adjusted to 7·5–8·0 with a few drops of dilute NaOH. The kaolinite was repeatedly centrifuged, decanted, and distilled water added until the supernatant liquid was free from Cl^-, and then sufficient NaOH was added to deflocculate

the clay. The chloride-free, deflocculated clays were made up into suspensions of known concentration. Calcium-saturated, chloride-free clay suspensions were obtained by repeated washing of the sodium-saturated clay with 0·01 M $CaCl_2$, and then dialysing at pH 7·5–8·0 (adjusted with half-saturated $Ca(OH)_2$). Ferric saturated illite was obtained by washing the sodium-saturated clay with a solution of 0·7 N $FeCl_3$ at pH 3.

3. *Wetting Tests on Dry Material*

Flakes (about 200 mg.) of clay, or soil crumbs (2–3 mm.) oven dried at 150° C. were used for the following tests:

(*a*) Wetted with distilled water in air.

(*b*) Wetted with distilled water in a dry vacuum. The material was over P_2O_5 in a desiccator at 4 mm. mercury for 30 min. before water was admitted from an external source.

(*c*) Wetted with distilled water in a humid near-vacuum. The material was over (i) distilled water, or (ii) saturated barium nitrate in a desiccator at 17 mm. mercury. Water was admitted as in (*b*); and other flakes were taken out of the desiccator and immersed in water in air.

Results

Test (*a*). From all materials there was escape of air bubbles. Illite immediately shattered into thin needle-like laths.

Montmorillonite Kaolinite Grundite	Immediate peeling into large fragments
Barnfield soil Willalooka subsoil	Immediate breakdown into small particles
Western Turville soil Gault clay	Peeled slowly into large particles.

Test (*b*). Exactly the same as for test (*a*) *except* for the absence of air bubbles. The shattering of a Ca-illite flake is illustrated in Plate I*a*.

Test (*c*). All clays remained stable, including the Barnfield clay. The Barnfield soil crumbs slumped into large fragments when removed from the desiccator and immersed in water. Plate I*b* shows a Ca-illite flake immersed in water in the air after exposure in an atmosphere of 98 per cent. relative humidity and 17 mm. mercury for 30 min.

Conclusions from wetting experiments

Comparison of tests (*a*) and (*b*) shows that dry crumbs slake whether air is present or not, i.e. entrapped air is not a necessary factor in slaking. Comparison of (*b*) and (*c*) shows that when the clays have taken up a small amount of water slowly they remain stable in water in the air. Combining (*a*), (*b*), and (*c*) it is inferred that entrapped air has no effect on the slaking of clays and that the action is dependent on rapid water uptake (presumably on rapid swelling) by the dry clay. If the initial wetting (and swelling) is slow the clay is stable to subsequent flooding.

A residual effect attributable to entrapped air is shown in the Barnfield soil crumbs, but this effect has been observed only with arable soils devoid of any organic or inorganic cementing materials. Similar soils examined by Quirk (1950), using a wet sieving technique, had a stability greater than 90 per cent. if wetter than pF 4·2 at the time of immersion.

4. *Orientation as a Factor in Breakdown*

Thin flakes (*c.* 200 mg.) of clays, prepared by pouring suspensions on to a sintered glass disk under suction, drawing off the water from below, and drying over P_2O_5, were used as follows:

(*a*) Immersed in distilled water, ethyl alcohol, and benzene, and behaviour noted.

(*b*) Thin sections of Na-montmorillonite were cut perpendicular to the plane on which the flake had dried and mounted on the stage of a polarizing microscope so that the plane of the cut was normal to the axis of the microscope. A few drops of 0·05 N NaCl were added, and the optical properties of the wetted flake observed.

(*c*) Areas (*c.* 10 × 10 mm.) were cut out, weighed, and linear dimensions measured to give bulk density (Table 1).

(*d*) Small flakes (1 cm.²) of dry sodium and calcium-saturated clays were wetted with N NaCl and 0·01 M $CaCl_2$, respectively, in an evacuated desiccator for 24 hours. Measurements of thickness were made at the beginning and end, using a travelling microscope reading to 0·002 mm.

Similar measurements were made on other clay flakes immersed in alcohol and benzene.

Results in Table 1 are the means of 4 replicates.

(*e*) Flakes of Ca-montmorillonite and Ca-illite were heated at 400° C. for 2 hours. When cool (i) their behaviour in water was noted, and (ii) their swelling in 0·01 M $CaCl_2$ after 24 hours was measured (Table 1).

TABLE 1

Swelling of Clay Flakes in Electrolyte, Alcohol, and Benzene

Clay	Dry density (g. cm.⁻³)	Thickness								
		Dry (cm.)	Wet (cm.)	Increase (%)	Dry (cm.)	Wet (cm.)	Increase (%)	Dry (cm.)	Wet (cm.)	Increase (%)
		N NaCl			C_2H_5OH			C_6H_6		
Na-montmorillonite	2·24	0·0107	0·0239	112	0·0156	0·0193	24	0·0153	0·0162	6
Na-illite	1·79	0·024	0·032	33	0·0220	0·0243	10	0·0243	0·0240	0
		0·01 M $CaCl_2$								
Ca-kaolinite	1·37	..	..	..						
Ca-grundite	2·15	0·0815	0·1765	111						
Ca-montmorillonite	..	0·0120	0·0218	82	After heating to 400° C.					
Ca-illite	..	0·0303	0·0302	0						

Results

Test (*a*) (i) In water.

Illite—No shattering but some breakdown, much less severe than in test 3(*a*).

Montmorillonite Kaolinite Grundite	Some breakdown, but much less rapid and less pronounced than in 3(*a*).

(ii) In alcohol. Some breakdown, but less severe than in water.
(iii) In benzene. All flakes stable.

Test (*e*) (i). The flakes heated to 400° C. were completely stable in water.

Test (*b*). No structure was observable in ordinary transmitted light at magnification × 60. Between crossed Nicols there was transmission of light, the intensity and pattern of which changed as the stage was rotated. At 90° intervals, when the *c*-axis of the sedimented clay was parallel to either of the Nicols a system of light and dark bands appeared across the sample, persisting over an angle of about ±12° on either side of the position of maximum contrast. (See Emerson (1956) for a more detailed description.)

5. *The Swelling of Oriented Flakes*

Test 4 (*c*) and (*d*). The bulk densities of the Na-montmorillonite and the Ca-grundite (Table 1) indicate very close packing, and with test 4(*b*) imply very regular orientation. The illite and the Ca-kaolinite are not so tightly packed.

The swelling data in Table 1 strongly suggest that degrees of stability noted in test 4(*a*) are associated with degrees of swelling, e.g. there is negligible swelling in benzene, and no instability; there is slight swelling in alcohol, and slight instability; there is considerable swelling in the polar liquid, and considerable instability.

The swelling of montmorillonite (Table 1) is in general accord with X-ray data. Norrish (1954) showed that in N NaCl the d_{001} spacing increased from 9·6 to 19·0 Å. with the uptake of three layers of water molecules between each pair of unit Si-Al-Si sheets, i.e. the thickness of a dry sample, in which the crystals are regularly stacked, should increase to just less than double its initial thickness. The observed increase is a little greater (to 2·12 times the dry thickness).

For the illite it seems necessary to invoke a different swelling mechanism. Repeated attempts to observe increased X-ray spacing of this material have all failed, suggesting that there is no regular interleaving of unit sheets of mineral with layers of water. Taking the thickness of a monolayer of water as about 3 Å., this is one-third of the thickness of the unit Si-Al-Si sheet, and hence the observed swelling (to 4/3 times the dry thickness) indicates that if the basic clay cell has n unit Si-Al-Si sheets, then, on average, there are n layers of water associated with each basic cell. As the theoretical surface area of the silicate sheet is 800 m.²/g., the wetted area of the illite will be $800/n$ m.²/g. Available estimates of the surface area of this illite (Quirk, 1955) are near 130 m.²/g., suggesting that n is near 6.

Presumably the water uptake here is a capillary phenomenon, and as there is no reason why the same thing should not happen in the montmorillonite the excess swelling there may be a measure of such capillary water between the clay particles.

6. *The Rate of Uptake of Water by Clay Flakes*

Thin flakes of acid-washed, chloride-free clays were prepared as in section 4. Samples of about 150 mg. were weighed dry and then exposed to the atmosphere above saturated barium nitrate at a temperature maintained within $\pm 0{\cdot}2^{\circ}$C. of 25°C., in a vacuum desiccator at 15 mm. of mercury. Rapid weighings were made at 0, 10, 20, and 30 min., and then after longer intervals until the weight of the samples was approximately constant. Some of the samples after exposure for 10 min. were immersed in water and all were completely stable.

The results (Table 2) are given as percentage increase on dry weight.

TABLE 2

Rate of Uptake of Water from an Atmosphere at 98 per cent. Relative Humidity

Time (min.)	10	20	30	90	330	1350
Material	%	%	%	%	%	%
Na-montmorillonite	9·7	12·5	17·6	25·0	27·6	34·5
Ca-montmorillonite	15·4	16·3	18·6	22·2	26·3	31·0
Na-illite . .	11·0	13·4	14·8	25·2	..	..
Ca-illite . .	11·1	13·7	16·6	24·3	28·1	28·9
Fe^{+++}-illite . .	9·6	12·1	14·3	25·0	27·2	29·6
Ca-kaolinite . .	2·0	2·0	2·5	..	..	3·2
Ca-grundite . .	10·0	13·6	15·6	..	..	22·0

It is generally accepted that the extent of water absorption by clays is controlled by the exchangeable cations which have fixed positions in the basal planes between unit cells, at the broken edges, and on the faces of clay flakes.

The illite and montmorillonite have taken up about the same weight of water at the end of 10 min. (Table 2), but the distribution of this water is unlikely to be the same in these clay minerals. Montmorillonite has an expanding *c*-axis, so that from the known surface area (800 m.²/g.) it is possible to calculate the thickness of the water layers, *w*, at any time; and, assuming for one layer $w \simeq 3$ Å.; for two $w \simeq 6$ Å.; and for three $w \simeq 9$ Å. (Bradley, Grim, and Clark, 1937), the thicknesses can be converted to numbers of layers. On this basis the results in Table 2 show that one monolayer of water molecules interleaves each of the Ca-montmorillonite crystals (somewhat less for the Na-montmorillonite) at the end of 10 min., and about three monolayers have been adsorbed after 1,350 min. Diffraction data indicate that this illite has a non-expanding lattice, so that water would be adsorbed primarily on external surfaces, and intercrystalline swelling only would occur (as distinct from the orderly intracrystalline swelling of the montmorillonite). The water adsorbed by the illite at the end of 10 min. (Table 2) corresponds to five monolayers per unit cell of this mineral, assuming a surface area of 130 m.²/g. The kaolin adsorbed little water vapour in agreement with a low base exchange capacity, and non-expanding lattice for this clay.

7. *Discussion and Conclusions*

There are two time scales involved in the preceding experiments. The flooding that sometimes produces slaking takes effect within seconds: the uptake of water vapour takes minutes (or hours). The first could produce impulsive forces within the clay, either by compression of trapped air (possibly augmented by temperature rise produced by release of heat of wetting), or by rapid swelling of the clay. An explosive air pressure would be effective whatever the orientation of the particles in the system, and, within the limits encountered here, whatever the size of the particles, i.e. it ought to be as effective on partly swollen clays as on those completely dry. A rapid swelling could produce graded effects depending on orientation, for one can imagine a perfectly packed array of uniform plates expanding rapidly in one direction only and yet retaining its identity; while in a random, less dense packing the impulsive swelling forces could produce turning moments that would be disruptive.

If however, on the long time scale, the rate of water uptake is slow, then these local forces might be locally dissipated by relative motion of the particles into positions in which the stress is relieved but coherence is maintained.

The evidence in this paper, and from elsewhere, supports this general outline of possibilities. First (section 3 (*a*) and (*b*)), it is clear that dry clay flakes will slake whether they contain air or not; second (section 3(*c*)), they do not slake even when the pore-space is air filled if they have been exposed to a humid atmosphere for long enough to induce some swelling; third (section 4(*a*)), the better the orientation of the clay (comparing flakes prepared on sinters or in evaporating dishes, or clay of different bulk density) the less violent is the disruptive action of flooding; and fourth (section 4 (*a*) and (*e*)), where there is no swelling there is no slaking, e.g. in benzene, or of illite after heating to 400° C.

It seems reasonable to conclude that the major and general cause of slaking is rapid swelling.

Tables 1 and 2, supplemented by some data from Orchiston (1954), can demonstrate another contrast between the swelling of the montmorillonite and the illite. Immersion in N NaCl corresponds to exposure to an atmosphere at 97 per cent. relative humidity, i.e. the equilibrium state for Table 1 should be somewhat drier than that for Table 2. Equating them for the moment, it becomes possible to derive information about changes in pore space during swelling. It is clear from Table 2 that final equilibrium was far from being attained, but reasonable extrapolation combined with Orchiston's data (his fig. 1) suggests that the limiting value of the water content would be about 45 g. per 100 g. for the montmorillonite and about 30 g. per 100 g. for the illite. Because of the difference in the thermodynamic potentials these quantities will be overestimates of the water taken up in the experiments that led to Table 1.

For the montmorillonite, 100 g. of dry clay will occupy 44·5 cm.^{3}, of which 38·5 cm.^{3} are solid, leaving 6·0 cm.^{3} occupied by air (pore

space = 14 per cent.). After swelling, the new volume is at least 2·12 times the dry volume (there is a little lateral swelling too), i.e. it is at least 94·5 cm.^{3}, and as the solid volume remains at 38·5 cm.^{3}, the volume of water plus air must be at least 56·0 cm.^{3}. The water uptake is estimated as no more than 45 g., and assuming its density is unity, the volume of air in the swollen flake is at least 11 cm.^{3}, i.e. the air-filled pore space is at least 12 per cent. of the volume of the wet flake. This is near enough to the initial value to suggest that there has been no major change, and is the behaviour to be expected if the clay platelets are regularly stacked and the water interleaves the platelets but does not collect in the cavities between the stacks.

The illite presents a different picture. The dry volume of 100 g. is 56 cm.^{3}, of which solid occupies 38·5 cm.^{3} and air 17·5 cm.^{3} (pore space = 31 per cent.). The wet volume is at least 75 cm.^{3} leaving water and air to occupy 36·5 cm.^{3}. The water uptake is no more than 30 g., so the air content is at least 6·5 cm.^{3}, i.e. the air-filled pore space is at least 9 per cent. of the volume of the wet flake. This suggests that the water is filling cavities in the illite, so reducing both the absolute and relative air content. Dr. Norrish presumes that many of the exchangeable cations are situated at the edges of the illite crystals, so that a reduction in pore-space between cells in an oriented flake would be expected when these cations become hydrated. Further work, in which volume and weight changes are measured on the same sample, will be needed to turn these speculations into certainties.

The purpose of Table 2 is to demonstrate the initial stage of uptake rather than the limiting conditions. Accepting the order of magnitude of the final uptake, the montmorillonites have taken up about one-quarter and the illites about one-third of the final uptake in 10 min. There is no knowing where the first water molecules go, but their effect seems to be clear: some internal readjustment of particle geometry takes place that renders the clay stable against subsequent flooding. The protective effect of exposure to water vapour may be produced in less than 10 min., and be of considerable importance in field behaviour. Rain or irrigation water falling on a dry soil will cause dispersion, either by mechanical pulverization or by slaking, but ahead of the slowly moving wetting front of liquid there will diffuse water vapour. A few minutes' exposure to such vapour is all that is needed to produce the protective conditions obtained by slow initial swelling, and hence the surface pan caused by flooding is confined to a very thin layer of soil.

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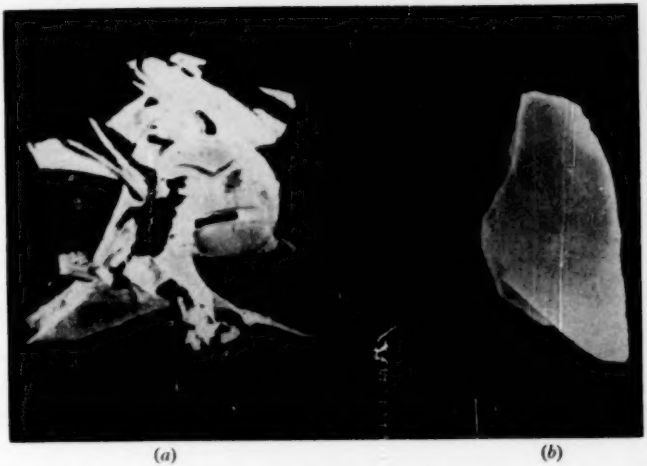
APPENDIX

THE ELECTRO-CHEMISTRY OF WILLALOOKA ILLITE

DURING consideration of the possible causes of the swelling of the illite some thought was given to the possibility that it might be behaving in the same way as the montmorillonite, i.e. by taking up layers of water between basic sheets. As the properties of illites appear to be much more variable than those of montmorillonites (Grim, 1953), chemical data for the material used were obtained from Dr. Norrish. His analysis is in Table 3, with some of his notes.

Notes. The cation exchange capacity of $< 2\,\mu$ fraction is 55 m.e./100 g. This clay is one of a series from Mallee soils which are dominantly illite but which have low K_2O and high cation exchange capacities. On those samples where there is sufficient data, there is an equivalent inverse relationship between K_2O and



(*a*) (*b*)

(*a*) Dry flake of Ca-illite immersed in water *in vacuo*
(*b*) Ca-illite flake allowed to take up water vapour at 98 per cent. r.h. prior to immersion in water in air

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exchange capacity. This is not due to inter-stratification since it cannot be detected from the diffraction data.

TABLE 3

Silicate Analysis of Willalooka Illite < 70 mμ (K. Norrish)

	Percentage Composition
SiO_2	49·05
Al_2O_3	23·00
Fe_2O_3	10·88
MgO	2·57
K_2O	4·00
H_2O	9·90

The low K_2O and high cation exchange capacity is probably due to replacement of K_2O by other ions at the edges of the crystals. The extremely small particle size (75 per cent. of the $< 2\ \mu$ fraction is $< 0{\cdot}1\ \mu$ and 46 per cent. is $< 0{\cdot}05\ \mu$) would favour this.

From this chemical analysis an attempt was made to assess the charge distribution, using Marshall's technique (1949, p. 58), on the basis of a total of 44 g. equivalents of cationic constituents per unit cell. The result, fourth line in Table 4, appears with three others given by Marshall.

TABLE 4

Elements and Charge Distribution in Clays

Material	*Elements present in*		*Charge (equivalents per unit cell) in*	
	Si *layers*	Al *layers*	Si *layers*	Al *layers*
Wyoming bentonite 50–100 mμ	Si, Al	Al, Fe, Mg	−0·41	−0·36
Montmorillonite < 200 mμ	Si, Al	Al, Fe, Mg, Ti	−0·02	−0·62
Illite (fine colloid)	Si, Al	Al, Fe^{+++}, Fe^{++}, Mg	−1·27	−0·19
Willalooka illite < 70 mμ	Si, Al	Al, Fe, Mg	−1·14	−0·12

Marshall (1937) infers that the rate of water vapour adsorption depends on the distribution of charges between the tetrahedral and octahedral layers of clay minerals. It is therefore suggested that the concentration of charge in the outside silicon layers of the Willalooka illite would permit a more rapid uptake of water than occurs with the montmorillonite, where the charge is more deeply buried in the cell lattice.

THE NATURE OF THE DRAIN CHANNEL AS A FACTOR IN THE DESIGN OF A LAND-DRAINAGE SYSTEM

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Summary

Drainage theory is customarily discussed on the assumption that the drainage channel is uniformly permeable. In practice such channels often consist of short lengths of relatively impermeable pipe separated by gaps. It is shown here that the appropriate modification to the theory in order to embrace such channels is to substitute an equivalent permeable channel of smaller radius.

Experiments described here enable one to evaluate the equivalent drain radius, and show that this radius is not solely dependent upon the geometry of the gappy channel but is markedly affected by the ratio of intensity of rainfall to soil hydraulic conductivity. In the examples shown a tenfold increase of rainfall rate causes a hundredfold increase of effective drain radius.

DURING the last decade considerable advances have been made in the theory of the design of drainage systems for the protection of land against locally incident precipitation.* There is an acceptable mathematical analysis (van Deemter, 1950; Engelund, 1951) which relates the height of the water table to the various relevant factors for the special case of infinitely deep permeable soil. These factors include the intensity of rainfall and artesian inflow, the hydraulic conductivity of the soil, and the diameter and separation of the drain channels. Furthermore, for particular cases where this analysis is not strictly applicable, as for example where there is an impermeable bed at a known depth, there are methods of arriving at specific solutions; these methods employ successive approximation and include relaxation and electric analogy. Two features are common to all these approaches. Firstly it is supposed that the flow of ground water to the drains has attained a steady state and secondly it is assumed that the problem is two-dimensional, i.e. that there is no variation in a direction parallel to the drain lines. It is with the second of these assumptions that the present paper deals.

In practice one very obvious kind of variation in the direction of the drain line is imposed by the nature of the drain channel itself. With the exception of mole drains (and the drainage of heavy clays in which mole drains are commonly drawn is a rather special case) the typical drain channel consists of a number of short lengths of relatively impermeable pipe separated by gaps of casual width consequent upon the butting together of ends which are but imperfectly perpendicular to the axis of the tubes. The material of the pipes may be baked clay, concrete, bitumenized fibre or cardboard and other similar substance, including recently polythene sheet and tubing. In so far as channels of this kind are a departure from the conditions assumed in developing current drainage theory, it is necessary to consider the effect of such departure.

* For a general account of the present state of knowledge about drainage matters see Luthin (ed.), 1958.

Two courses lie open to us. Firstly one might attempt to develop a strictly correct theory for a three-dimensional problem to include a treatment of the gappy pipe-line. This course would appear to be formidably difficult; the two-dimensional case is sufficiently forbidding. Secondly we may attempt to modify the two-dimensional theory by ascertaining the particular factor or factors through which the gappiness of the pipe-line makes its effect felt. It may be remarked here that the modification of the rate of flow into a drain, due to gappiness of the pipe-line, from a soil with boundaries maintained at a known hydraulic potential (as when the soil surface is ponded) has been studied by Kirkham (1950), by Kirkham and Schwab (1951), and again by Ede (1958). Our purpose is rather to study the circumstances when the drain is performing its assigned function of controlling the water-table height in the face of imposed surface precipitation such as rainfall, and particularly to study the effect of the gappiness on the height of the water table.

The General Nature of the Effect of Channel Linings

A channel lining is provided for the sake of the mechanical support it provides, maintaining a path of free flow for water through mechanically weak soil. Hydraulically its effect on the flow of water through the soil to the drain is that of a zone of material, the hydraulic conductivity of which differs from that of the soil. We may distinguish three particular cases; (*a*) the lining has a conductivity so much greater than that of the soil that it may be regarded as offering no resistance to the flow of water to the drain channel; (*b*) the lining conductivity approximates to that of the soil; and (*c*) the conductivity of the lining is so much less than that of the soil that it may be regarded as an impermeable barrier. In case (*a*) the lining has no other function than mechanical support and the effective drainage channel may be taken to be uniform in the direction of its length and of a diameter equal to the outside diameter of the lining. In case (*b*) the lining is indistinguishable from the soil in which it is laid so far as its hydraulic conductivity is concerned, and again the effective channel may be taken as uniform in the direction of its length, but its effective diameter is now that of the inside of the lining. Case (*c*), which is the commonly occurring one, differs fundamentally from the others in that the lining presents a barrier to flow except at the gaps between pipe sections, and the flow to the channel is concentrated into these gaps. There is no longer uniformity in the direction of the drain line. Two different modifications of this case are distinguishable.

The situation is not easily illustrated by a diagram, but Fig. 1 is a perspective view of a drain line *AB* beneath a water table *CDEF*, issuing from which are some exemplary sheets of streamlines *EABF* and *DABC* which contribute their flow to the channel via one or other of the gaps *A*, *H*, and *B*. Figs. 2*b* and 2*c* show a sheet such as *DABC* flattened out in the plane of the paper. Fig. 2*a* shows a similar sheet for the case where the drain is an unimpeded soil boundary such as is assumed in the analysis of two-dimensional drainage problems. In the conventionally assumed circumstance that the drain is just full of water

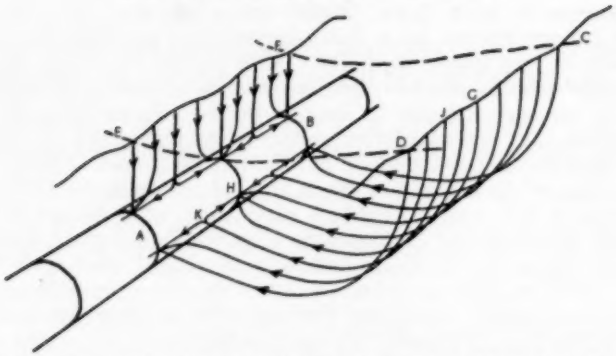

FIG. 1. Perspective view of streamlines from water table to drain line.

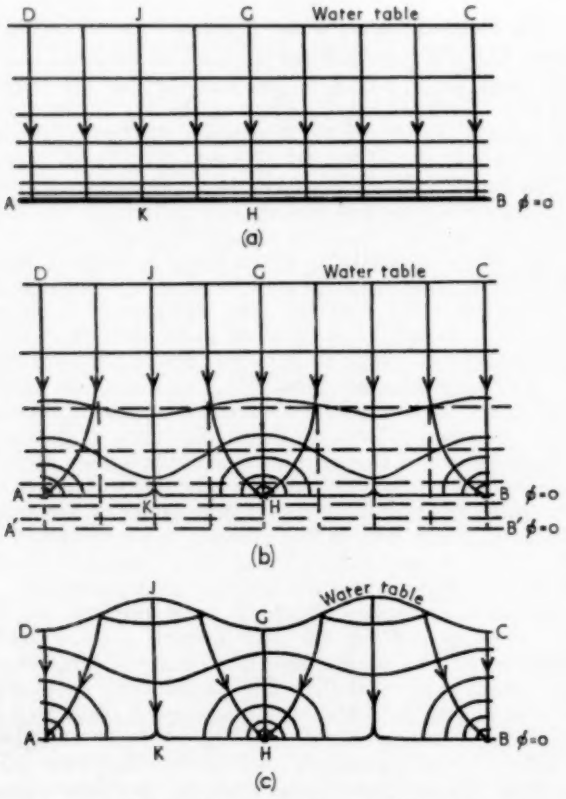

FIG. 2. Sheets of streamline developed from Fig. 1.

without back pressure, the drain perimeter is an equipotential surface which may for convenience be taken as the arbitrary zero equipotential. Thus in Fig. 2*a* the drain AB is a surface at zero potential and the water table CD is a parallel surface at uniform potential ϕ_ω lying at a vertical height h_0 above the water table, so that

$$\phi_\omega = h_0.$$

The equipotentials form a family of straight lines perpendicular to the streamlines, i.e. parallel to the drain line and water table. The equipotentials are closer together the nearer the drain because the flow of water to the drain is concentrated in a smaller cross-sectional area of soil and by Darcy's law requires a steeper potential gradient.

In Figs. 2*b* and 2*c* we see that the streamlines converge into the gaps between pipe sections. By symmetry the streamlines DA, JK, GH, &c. are straight lines (in the developed sheet) parallel to each other and perpendicular to the drain line, and the intermediate streamlines must also tend to become similarly parallel as they become sufficiently remote from the drain channel, in order to satisfy Laplace's equation to which Darcy's law gives rise. Fig. 2*b* shows the case where the water table is sufficiently remote from the drain line for this to be able to happen, while for Fig. 2*c* such is not the case. In the former case we see that the equipotentials near the drain line curve round the gaps but become parallel to the drain at a sufficient distance. It cannot, of course, be assumed that the flow net beyond this distance is identical with Fig. 2*a* but it may be extrapolated back towards the drain in such a way as to satisfy the two-dimensional form of Laplace's equation, as shown by the broken lines, as far as the eventual boundary $A'B'$ given by the zero equipotential, which does not, of course, coincide with the actual drain AB. That is to say we may construct a hypothetical flow-net which would be appropriate to an unimpeded drain surface and which would give the same water table and neighbouring flow-net as that actually produced by the flow to the gappy drain line. We have thus shown that it may be expected that the water-table location may correctly be found by an application of the known two-dimensional theory provided that instead of the actual drain channel we substitute an ideal unimpeded drain channel surface of some different radius. It may be remarked here that there is nothing in the argument above to lead us to suppose that the envelope of all the lines such as $A'B'$ bounding all the sheets such as $ABCD$ will be a cylindrical surface or indeed any regular shape, and only the development of a stringent three-dimensional analysis would enable us to arrive at the shape on theoretical grounds. But then it must be said that the hodograph theory of the two-dimensional case does not itself cater for initially specified cylindrical drains, for the drain surface only emerges as a particular equipotential surrounding a line sink at infinitely large negative potential. It just so happens that the equipotentials in the neighbourhood of this sink are sufficiently close approximations to circular cylinders for the results to be taken as appropriate to cylindrical drain channels. We shall therefore suppose without further discussion that the envelope of the equipotentials such as $A'B'$ in Fig. 2*b*

is also sufficiently nearly cylindrical for the known theory to be applied. In any case we have shown that the appropriate way in which to take the gappy nature of the drain line into account in applying theory to this case is to substitute an equivalent unimpeded drain of different cross-section; whether this cross-section is to be considered circular is a matter upon which experimental evidence may be expected to throw some light.

In Fig. 2*c* it is not to be expected that any similar substitution as is described above will suffice. One of the consequences of the fact that at no part of the flow-net are the equipotentials parallel straight lines, parallel to the drains, is that the water table itself is not parallel to the drain but is wavy in form in this direction. The current two-dimensional theory naturally presents no such feature as this, and we must accept the fact that it simply is not applicable. One of the objects of experiment must be to discover how important in practice this limitation is; that is to say, how likely it is that such cases will arise in the course of practical draining. The purpose of the present paper is to present evidence confirming the conclusions arrived at above and to discuss the bearing of these findings on drainage practice.

Experimental Method

The experimental drainage tank of the Agricultural Research Council Unit of Soil Physics was designed to study just such three-dimensional problems as this. It has been described in detail elsewhere (Childs, 1953), but a brief description here may be convenient. It consists of a reinforced concrete tank of dimensions 10 m. × 10 m. × 1·5 m. filled with a very uniform sample of Leighton Buzzard sand, the hydraulic characteristics of which have been described by Childs *et al.* (1953). It is enough to say here that it has a saturated hydraulic conductivity of about 10^{-4} cgs. or 86 m. per day, although the actual value depends rather on the manner in which it is packed during the preparation of a particular experiment. There is provision for installing drains which are the equivalent of an infinite array of uniformly spaced channels at uniform depth; the ratio of separation to depth is variable within designed limits. The drain is laid down the middle and the impermeable side walls of the tank correspond to the medial plane between neighbouring drains of the infinite system. An overhead system of swirl-plate spray-nozzles fed with water from a constant head tower provides a sufficiently uniform precipitation at the sand surface at controllable intensity. Instrumentation includes a flow-meter for measuring the artificial rainfall rate; a drainage flow-meter developed from an earlier and smaller model (Childs, 1940) and calibrated by diverting the outflow into a standard volumetric reservoir and measuring the rate of rise of level of the collected water; and apparatus for recording the distribution at any moment of the hydrostatic pressure in the sand (Childs, 1953; O'Donnell *et al.*, 1958). The location of the water table is deduced from this pressure distribution, since it is that surface within the sand at which the hydrostatic pressure is zero.

For those experiments which required the use of a uniformly permeable drain channel, the type of channel lining used took the form of the

gravel-filled well casings described by Childs *et al.* (1953). For work with gappy impermeable linings we have used the same gravel-filled casings wrapped with impermeable sheet except for the gaps. In order to form each gap two strips of 31 s.w.g. phosphor bronze were held firmly flat on the bench parallel and edge to edge. The required gap width was obtained by separating the neighbouring edges by gauges of the necessary thickness while the strips were firmly soldered to wire cross-connectors. Each pair of strips was then wrapped round the drain lining at intervals equal to the required interval between gaps, and the remaining space between pairs of strips was filled in with bitumenized paper sealed to the phosphor bronze with adhesive plastic tape ('Sellotape'). The smallest gap width which could be formed in this way with acceptable accuracy was about $\frac{1}{64}$ in. (0·4 mm.).

Experimental Results

The drainage systems studied were of the kind shown in cross-section in Fig. 3. The drains are to be supposed to be at uniform depth and at uniform separation $2D$ in soil of uniform hydraulic conductivity K with a uniform rate of surface precipitation q. It is convenient to express all linear dimensions as fractions of D, and in particular the height h of the water table midway between drains, relative to the axis of the drain, will be expressed in the form of the ratio h/D. The precipitation rate is particularly significant in relation to the conductivity and will therefore be expressed as the ratio q/K, and for this purpose the definition and units of potential are chosen in such a way as to make the unit of K the same as the unit of q, namely 1 cm./sec.

It is inherent in the design of the sand tank that there is an impermeable floor at a finite distance below the level of the drain channel, whereas the available acceptable analysis deals only with the case of an infinitely deep floor. It has been found experimentally, however, that provided that the ratio d/D (where d is the depth of the floor below the drain) is greater than about 0·3 the floor is without influence on the height of the water table and might as well be at infinite depth. Such a value of d/D is not practicable in the full-sized tank, and recourse was had to scale model work in a subdivision of the tank, as described by Childs (1953), for those results reported below which refer to such floor depths.

In Fig. 4 are plotted two curves, both of which are for a value of d/D of 0·39 (effectively infinity) and for a uniformly permeable drain channel of such a radius r as gives a ratio r/D of 0·0305. Curve (*a*) plots h/D against q/K and curve (*b*) plots b/D against q/K, where b is the height of the water table immediately above the drain channel. Similarly Fig. 5 plots h/D and b/D against q/K in the same circumstances except that the drain has a gappy impermeable lining, with gap widths of the magnitude $w/r = 0{\cdot}0078$ and gap intervals of the magnitude $s/r = 2{\cdot}0$. Interpreted to full scale with drain separations of 10 m., the drain lining has radius 15 cm. and consists of impermeable sections of length 30 cm. separated by gaps of width 0·12 cm. In Fig. 4 is also shown the theoretical curve given by the hodograph analysis.

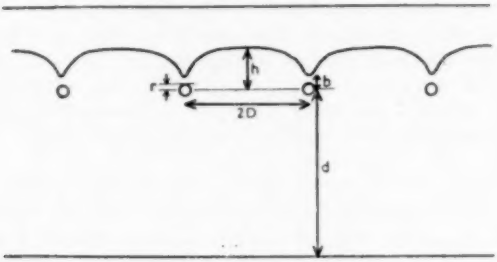

FIG. 3. Water table due to rainfall rate q on soil of hydraulic conductivity K with a drainage system, indicating the significant parameters.

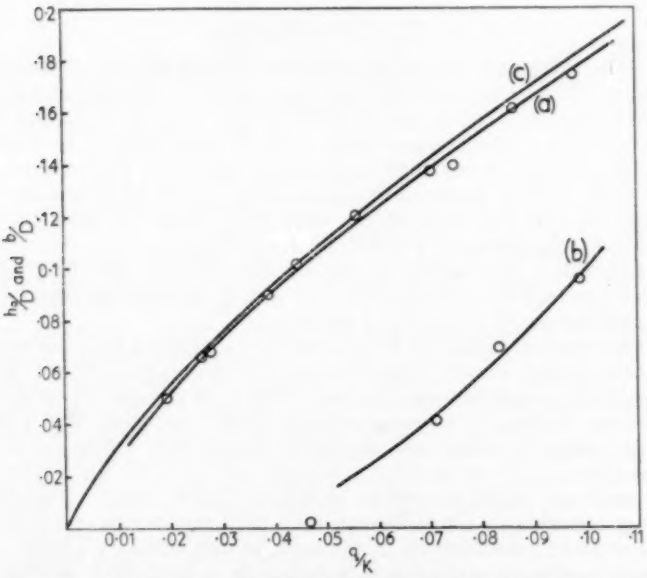

FIG. 4. Relationship between q/K and ratio of water-table height to drain separation for a continuous permeable drain channel; effective depth of impermeable floor is very large. $r/D = 0{\cdot}03$. Curve (*a*) Height midway between drains. Curve (*b*) Height over the drains. Curve (*c*) Theoretical height midway between the drains for optimum drain radius.

Figs. 6 and 7 are similar to Figs. 4 and 5 respectively except that we have the opposite extreme case of the drains laid directly on the impermeable floor, for which case there is, of course, no theoretical curve to be included in Fig. 6 for comparison. These experiments were carried out in the full-sized tank with full-sized drains. The value of r/D was 0·02 and two different widths of gap were used, with values of w/r of 0·0039 and 0·0156.

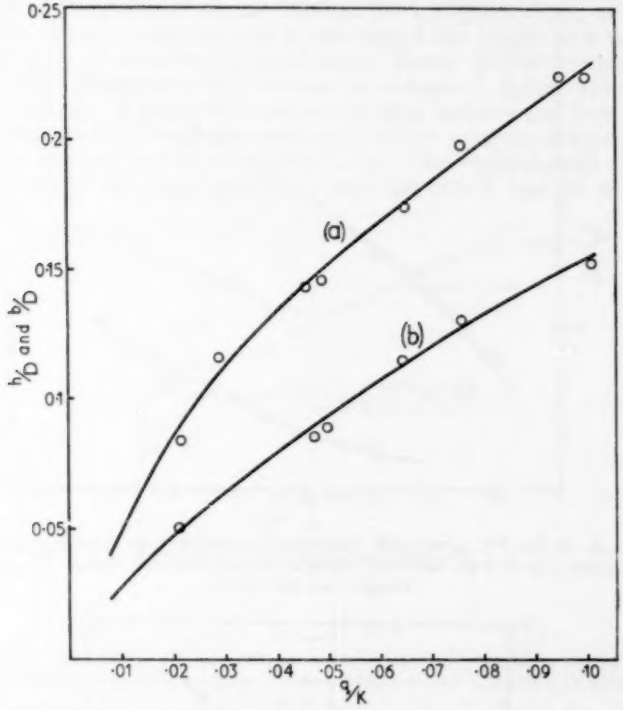

FIG. 5. As for Fig. 4 but with gappy impermeable drain channel. Curve (*a*) Height midway between drains. Curve (*b*) Height over the drains.

Discussion of Results

It is convenient first to refer to the essentials of the results of the analysis by conformal transformation as presented by van Deemter and by Engelund (loc. cit.). That analysis proceeds for a given value of q/K and D on the assumption that the drain is a line sink (i.e. with zero radius) at an infinitely negative potential. This latter condition is indeterminate and consequently there are an infinite number of solutions giving an infinite number of different water tables and corresponding potential distributions. Since by the definition of hydraulic potential

$$\phi = z + H, \tag{1}$$

where z is the vertical height above an arbitrary datum (taken as the axis of the drain for convenience) and H is the hydrostatic pressure expressed as a head of water, each equipotential in a given solution may be regarded as a surface for which may be substituted the perimeter of a drain subjected to back pressure due to being submerged under a given depth of water. Thus in a given flow-net resulting as any one of the

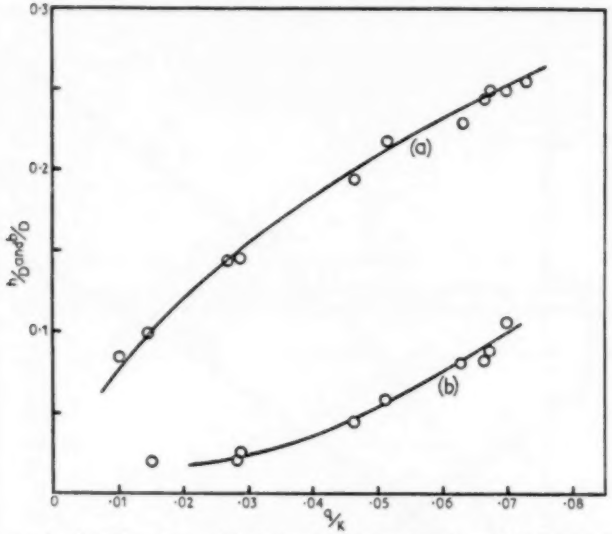

FIG. 6. As for Fig. 4 but with drains laid immediately on the impermeable floor and $r/D = 0{\cdot}02$. Curve (*a*) Height midway between drains. Curve (*b*) Height over the drains.

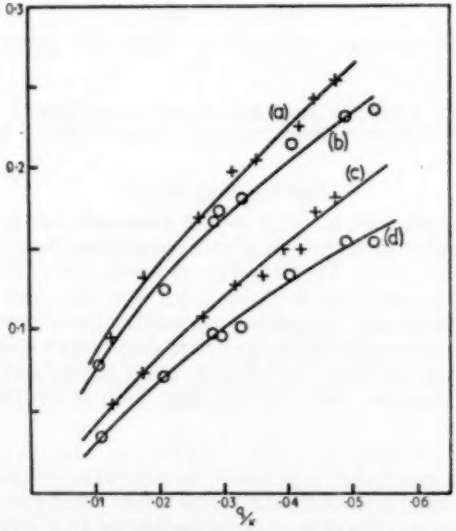

FIG. 7. As for Fig. 6 but with gappy impermeable drain channel. Curve (*a*) Height midway between drains, and curve (*b*) Height over drains: $w/r = 0{\cdot}0039$. Curve (*c*) Height midway between drains, and curve (*d*) Height over drains: $w/r = 0{\cdot}0156$.

solutions of the problem we may choose the equipotential ϕ_α as shown in Fig. 8. At any point on this equipotential the height is z and the pressure is $\phi_\alpha - z$ as given by equation (1) above. If this equipotential were a drain perimeter with its origin at a depth L below water level (as, for example, if its outfall were submerged below water level in the ditch), then the hydrostatic pressure at the given point on this perimeter which we are considering would be $L-z$. The equipotential and the drain perimeter are thus equivalent provided that L has the value ϕ_α.

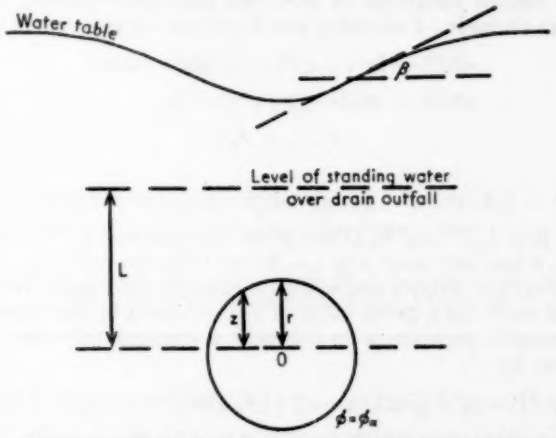

FIG. 8. Illustrating the equivalence between an equipotential at potential ϕ_α and the perimeter of a drain whose outfall is under a depth L of water. $L = \phi_\alpha$.

It is usual to suppose that the drain is just full of water when designing the system; if the water level in the channel is lower than the roof then the perimeter is a surface of seepage and not an equipotential, and consequently the flow-net and water table do not correspond to any of the solutions given by theory. It follows therefore, on this assumption, that the particular solution of all the many possible solutions for a given q/K and D is that for which the known drain channel perimeter whose roof is at a known height r above the axis corresponds to an equipotential the potential at which has the magnitude r, for at the roof of the channel the hydrostatic pressure is, by hypothesis, zero. In general there are two such equipotentials for each solution, one of which passes through the water table immediately above the drain axis at height b, since by definition of the water table the hydrostatic pressure is here zero, and the other is nearer to the axis. The equipotential through the water table is often a very unlikely candidate for the role of the drain perimeter on account both of shape and of size, but the possibility must be borne in mind.

Whilst the drain size is the third boundary condition which defines a particular problem and a particular solution, it is an unsuitable parameter for the analysis and has to emerge with the solution. One of the

effects of varying the drain size is to alter the maximum slope β of the water table (measured in the plane at right angles to the drain lines), and this angle can have any value between zero (for infinitely small drains) and 90° for an optimum drain size. This angle is the parameter chosen for specifying a particular case. For a value of 90° the two equipotentials which correspond to possible drain perimeters coincide, and the values of h/D and b/D are a minimum, for a given q/K. The values may be indicated by h_0/D and b_0/D for this optimum drain size; both quantities are single valued functions of q/K and may conveniently be plotted against that variable. Following van Deemter we may write

$$\left.\begin{aligned} \pi h/D &= \ln(1+2/\lambda)+(2/\gamma)\ln(1+\lambda/2) \\ \pi b/D &= \pi h/D-(2/\gamma)\ln(1+\lambda) \end{aligned}\right\} \qquad (2)$$

where

$$1+\gamma = K/q$$

and

$$1+\lambda = [(K/q)\tan\beta+\{(K/q)^2\tan^2\beta+1\}^{\frac{1}{2}}]/[\tan\beta+(\tan^2\beta+1)^{\frac{1}{2}}]$$

It follows that h_0/D and b_0/D are given by equation (2) for the special case when β has the value $\pi/2$, i.e. when λ has the value γ. The curve of h_0/D versus q/K so obtained is the theoretical curve indicated in Fig. 4. The size of drain for a given value of β is obtained in the following way. The hydrostatic pressure p at a height z immediately over the drain axis is given by

$$\pi p/D = (q/K)[\ln\{\delta/(2-\delta)\}+(K/q)\ln\{(\lambda+2-\delta)/(\lambda+\delta)\}] \qquad (3)$$

where δ is a parameter which is related to z by the equation

$$\pi z/D = [\ln\{(\lambda+\delta)/\lambda\}+(1+2/\gamma)\ln\{(\lambda+2)/(\lambda+2-\delta)\}+ \\ +(2/\gamma)\ln(1-\delta/2)] \qquad (4)$$

Since by hypothesis the drain is just full of water, the hydrostatic pressure at the roof is zero and hence δ has the value which gives p the value zero according to equation (3). This value of δ determines, in accordance with equation (4), the particular value of z which corresponds to the height r of the roof of the drain. To be strictly correct we should now find the depth of the floor of the drain by finding, in a similar manner, the depth at which the hydrostatic pressure is just equal to the depth below the roof of the drain as already found. This is necessary because it is not known *ab initio* that the equipotential which we are considering to be coincident with a drain perimeter is in fact a circle with its centre at the axis of coordinates. In practice the solution of a few problems is sufficient to convince one that for the usual small drain size it is a warrantable assumption that the axis of coordinates is also the axis of a cylindrical drain line, and that the value of r calculated above is the effective radius of the drain channel. It is found that the drain size for a given value of β depends upon the value of q/K, as indeed do also the values of h/h_0 and b/b_0, although the dependence is not marked except at small values of β. It follows from the discussion of the manner in which the drain features in the theory that when β has

the value 90° the drain meets the water table and its radius has the value b_0. Following Engelund (loc. cit.) we may therefore construct curves showing how r/b_0 depends upon β for selected values of q/K. For the range of value of q/K used in the present work a single curve suffices,

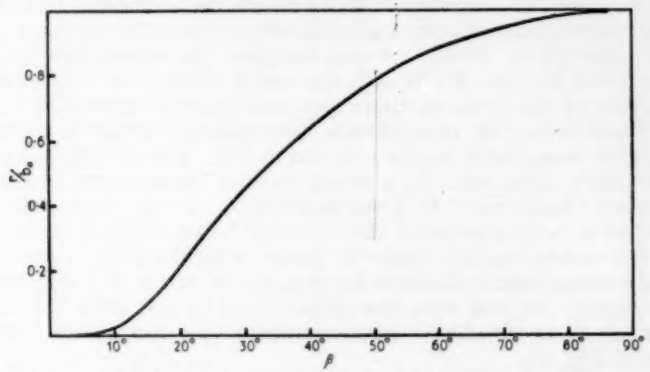

FIG. 9. Relationship between the steepest slope, β, of the water table and the ratio of drain radius to optimum radius. (After Engelund.)

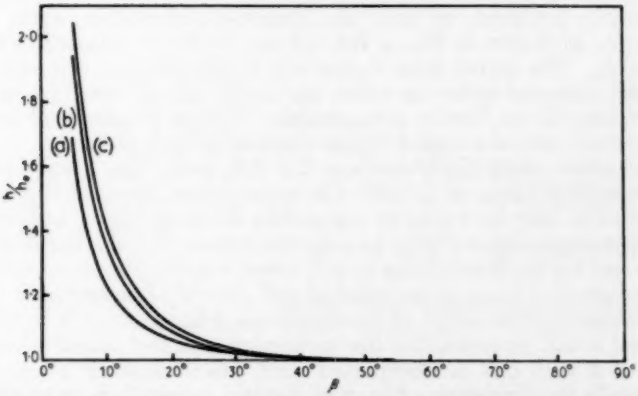

FIG. 10. Relationship between β and the ratio of the water-table height midway between drains to the height for optimum drain radius. (*a*) $q/K = 0{\cdot}01$; (*b*) $q/K = 0{\cdot}05$; (*c*) $q/K = 0{\cdot}10$. (After Engelund.)

and is shown in Fig. 9. This curve was presented by Engelund (loc. cit.), but that shown here has been recalculated and differs slightly from Engelund's at low values of β which are of importance to us. Again we may show how h depends upon β by plotting curves of the correcting factor h/h_0 against β, as in Fig. 10. We could similarly plot b/b_0 against β, but for reasons to be explained we do not find this a convenient factor for use. The general effect of a reduction in the value of β due to a reduction of the drain radius r is to raise the water table. However,

whereas the height h of the water table above the axis of the drain midway between drains is but little affected for a given value of the ratio q/K unless β is reduced below about 30°, the height b of the water table over the drains is sensitive to quite small reductions of β.

We now see that we have two independent measurements from which we may calculate the effective radius of a drain channel from observations of the water table. Firstly we may compare the water-table height at the midpoint between drains with that which we know to be appropriate to the case of the optimum drain size, and from the ratio h/h_0 find the value β and thence the value of r/D. Alternatively we may find the ratio b/b_0 for the water-table height over the drains. This is not, however, a very suitable ratio, since b_0 is small and not amenable to precise experimental observation. It is not desirable to use the unchecked theoretical value of b_0 because if there should be any departure from the boundary conditions for which the theory is deduced there would be a lack of correspondence between b and b_0 due in part to this discrepancy. Consequently we use here the dependence of the ratio b/h on the parameter β, as developed from equations (2); the curves used are shown in Fig. 11.

One final point calls for remark. It is not practicable to carry out experiments with an optimum drain radius for a range of values of q/K, for the optimum radius depends on the value of q/K. It is therefore not strictly justifiable to label the observed water-table height at the midpoint, as shown in Fig. 4 for continuous drain channels, with the symbol h_0. The actual drain radius was in no case, however, markedly different from the optimum value, and since h is not sensitive to small reductions of β the label h_0 is acceptable. The good agreement between the observed and theoretical values emphasizes this point.

For a given value of q/K one may find h/h_0 from Figs. 4 and 5 and the corresponding value of β from the appropriate curve of Fig. 10. A second value may be found by computing b/h from Fig. 5 and entering the appropriate curve of Fig. 11 with this value. Table 1 is constructed in this way for the three values of q/K listed, namely 0·01, 0·05, and 0·10. The values of β for a given value of q/K should of course agree if our interpretation of the effect of the gappiness of a drain line is the correct one, and it will be noted that the agreement is in fact satisfactory. The trend of β with q/K is unexpected, and indeed leads to a conclusion which calls for discussion. Col. 7 of Table 1 gives r/b_0 as read off from the appropriate curve of Fig. 9; col. 8 gives r/D from the product of the figures in cols. 7 and 8. It will be noted that one and the same gappy drain has an equivalent continuous drain the diameter of which depends not only on the geometry of the channel but also upon the value of q/K; for $q/K = 0{\cdot}01$, the ratio of the effective drain radius to the half spacing of drains is 0·00001, but for $q/K = 0{\cdot}1$, it is 0·00091, an increase of nearly a hundredfold for an increase in rain intensity of tenfold. It should be stated here that in all cases dealt with the water table was found to be without variation in the direction of the drain line, i.e. the waviness in this direction which would have invalidated the interpretation was absent.

The dependence of effective drain radius of a gappy drain lining on the value of q/K is also indicated by the shape of the curve of b/D versus q/K as shown in Fig. 5. We see in Fig. 4 for a continuous drain of defined radius that the curve is convex to the q/K axis, and it may be

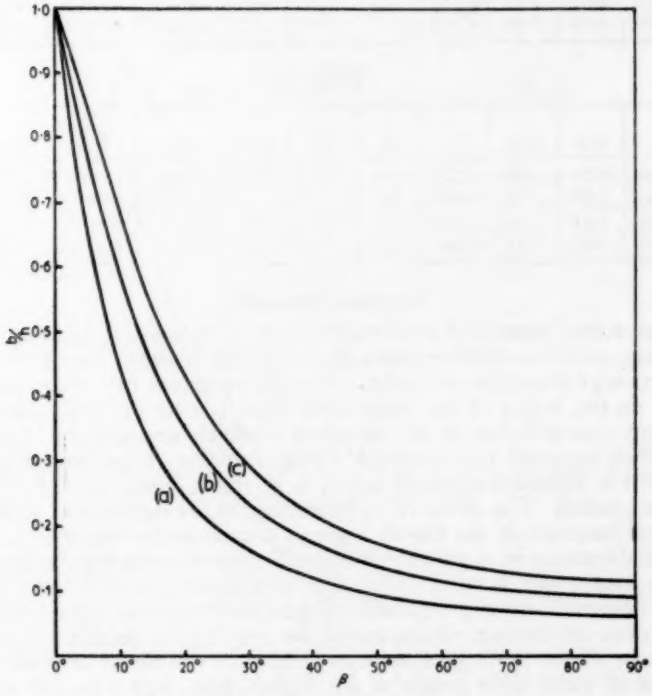

FIG. 11. Relationship between β and the ratio of the water-table height over the drains to the height midway between drains. (*a*) $q/K = 0{\cdot}01$; (*b*) $q/K = 0{\cdot}05$; (*c*) $q/K = 0{\cdot}10$.

shown that this is in accord with theory for a uniform drain of fixed radius. By contrast the comparable curve in Fig. 5 is concave to the q/K axis. That this is not exceptional, but is a truly repeatable experimental result, is shown by Figs. 6 and 7 where the same effect is seen. One cannot make quantitative estimates of drain radius in this case because the drain is laid directly on the impermeable floor, for which the mathematical analysis has yet to be developed. If, however, one makes the reasonable assumption that the shallow depth of an impermeable floor, while greatly affecting values of h, h_0, and b, has only a relatively slight effect on the ratios h/h_0 and b/h, we may draw up Table 2 in the same manner as Table 1 and, with caution, draw similar conclusions confirming what has been said above.

TABLE 1

w/r	q/K	h/h_0	b/h	β_h°	β_b°	β° *mean*	r/b_0	b_0/D	r/D
0·0078	0·01	1·78	0·561	4·5	6·9	5·7	0·005	0·0020	0·00001
0·0078	0·05	1·41	0·612	8·9	9·4	9·2	0·019	0·0102	0·00019
0·0078	0·10	1·27	0·675	12·8	10·3	11·6	0·042	0·0216	0·00091

TABLE 2

w/r	q/K	h/h_0	b/h	β_h°	β_b°	β° *mean*	r/b_0	b_0/D	r/D
0·0039	0·01	1·36	0·581	7·4	6·4	6·9	0·009	0·0020	0·00002
0·0039	0·05	1·35	0·722	9·9	6·3	8·1	0·011	0·0102	0·00011
0·0156	0·01	1·22	0·521	10·1	7·8	9·0	0·018	0·0020	0·00004
0·0156	0·05	1·22	0·676	13·3	7·5	10·4	0·031	0·0102	0·00032

General Discussion

One of the features of the results of the mathematical analysis of the drainage problem which favours the facility of drainage design is that a reduction of drain channel radius below the optimum value has a marked effect on the height of the water table directly over the drain, where it is in any case at its lowest and therefore relatively unimportant, but does not affect seriously the water-table height midway between the drains, where it is highest and can ill afford to be raised, until the reduction of size is marked. The effect of substituting for the uniformly permeable channel assumed in the theory a gappy impermeable lining as in most practical systems is, as we have seen, equivalent to reducing the diameter of the continuous channel. With gaps of sufficient width relative to the drain diameter and gap separation the reduction of the diameter of the equivalent continuous drain would be insufficient to affect the performance of the drainage system as judged by the practical criterion of control of water-table height at the highest part; and indeed it will be seen from the results presented above that the increase of this height due to the very narrow gaps used is not great. Nevertheless, it is not so negligible that one can ignore it with confidence in all circumstances.

In deciding what steps can be taken to take into account the gappiness of drain linings in practical systems one must bear in mind that the separation, but not the true width, of the gaps is under the control of the drainer. It would be unrealistic to expect the practising drainer to lay pipes with a specified separation at the butt joints; indeed, unless the pipes were of unusually good quality the irregularity of the ends would make such a feat impossible. It is therefore not possible to introduce the gap geometry as another controlled variable influencing the water-table height, and we have therefore not attempted to make the kind of thorough study which would be required to assess quantitatively the effect on the water table of a wide range of gap sizes.

The more satisfactory alternative is to ensure that the gaps are prevented from having their expected effect. This may be done by

increasing their effective width by depositing a highly permeable material such as gravel about the butt joints. The soil boundary at the drain is then as shown in Fig. 12; for the purposes of soil water flow the boundary consists of the impermeable sections *I* and the permeable sections *P*, and these latter act as sinks which easily drain via the gaps and therefore

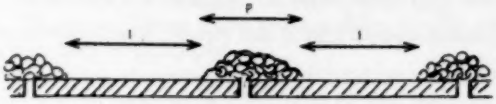

FIG. 12

constitute the effective gap widths. Any practicable means of depositing the gravel will ensure that *P* is comparable with *I* in length and that the value of *h* will be negligibly different from the ideal h_0. The point we wish to stress is that it is not necessary to backfill the whole length of the drain with gravel, thus ensuring a truly continuously permeable channel, to secure the important benefits of such permeable backfill. Since the importation of foreign permeable materials to a site is often an expensive item, this finding is significant.

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SOME FACTORS DETERMINING WATER-TABLE HEIGHTS IN DRAINED HOMOGENEOUS SOILS

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Summary

The effect of the depth of impermeable floor below the drain level on water table heights in homogeneous soils, drained by a uniform system of ideal drains, for steady state conditions with various rainfall intensities, was investigated by means of hydraulic model and electric analogue experiments. Agreement was obtained between the two series of experiments which indicated that, for a given ratio of rainfall intensity to hydraulic conductivity, the water-table height midway between the drains decreased as the depth of the impermeable floor below the drain was increased from zero, tending towards a constant height when the ratio of the depth of the impermeable floor below the axis of the drain tube to the half spacing of the drains approached 0·3. In addition, in the experiments with a deep impermeable floor, agreement was found with the analytically obtainable solution of the problem with an infinitely deep floor. Water-table heights observed in the non-steady state hydraulic experiments approximated to those of the steady state with uniform distributions of flux cutting the water table for corresponding equal mean distributions, calculated from the drain discharge.

QUANTITATIVE work on drainage design has been based on solutions of Laplace's equation which describes the potential distribution in the ground-water zone. Two methods of approach have been used. First there is an analytical method based on the construction of the hodograph of the problem (van Deemter, 1950; Engelund, 1951). Secondly there are successive approximation methods, including relaxation (van Deemter, 1950) and electric analogy (Childs, 1943, 1945*a*, *b*, 1947; Childs and O'Donnell, 1951; Edwards 1956). In such work the drains are assumed to be laid at a uniform depth above the impermeable floor with a uniform spacing in soil of uniform hydraulic conductivity; in the analytical method the impermeable floor is assumed to be infinitely deep. Solutions are obtained for a steady-state condition (that is, when the drain discharge equals the steady rainfall applied at its surface) with the drain running just full, although the electric analogue has been used to solve the non-steady state problem of the falling water table (Childs, 1947) and the rising water table (Childs and O'Donnell, 1951). However, the latter work is concluded with the statement: 'The technical difficulties of this particular experiment were such that the work described appears to have reached the limit of usefulness of the analogue method', which implies its limited use. The capillary fringe above the water table can be taken into account in the successive approximation methods, but its effect has been shown to make little change in the water-table height at least for high water tables (Childs, 1945*b*). It is excluded from consideration in this paper to simplify calculation and experimental

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procedure. Further work, which will be reported in a later paper, is being conducted on this problem in this laboratory.

It is pertinent to see how the above approaches compare with the actual hydraulic problem which they attempt to solve. It is also of practical consequence to see how observations on the non-steady state, the common occurrence in nature, deviate from the solutions of the steady state. These problems have been tackled in the sand tank with which this laboratory is equipped.

In drainage design dimensional considerations indicate that it is convenient to express lengths as a fraction of the half-spacing D of the drain tubes and the flux q cutting the water table as a fraction of the saturated hydraulic conductivity K of the soil. Thus the factors which are of interest in drainage problems are the ratios h/D, d/D, and q/K, where h and d are respectively the height of the water table midway between the drain tubes and the depth of the impermeable floor, measured from the drain axis. For a drain of optimum radius the hodograph method gives a unique curve for values of h/D plotted against q/K for the case where d/D approaches infinity. The successive approximation methods are able to give a correction factor for other values of d/D. The effect of drain diameter on the water-table height has been discussed by van Deemter (1950) and Engelund (1951), but in this paper we shall be concerned only with drains which can be considered as having the theoretical optimum drain diameter as far as the ratio h/D is concerned.

The Hydraulic Experiments

The experimental sand tank, measuring $10 \times 10 \times 1{\cdot}5$ m., which was used in the hydraulic experiments, has been described in detail by Childs (1953) and by Childs and Youngs (1958). The tank is filled with uniform Leighton Buzzard sand of saturated hydraulic conductivity of about 125 in./hr. (about 0·09 cm./sec.), on which uniform rainfall can be simulated by means of a grid of nozzles. Outlets are provided for drains to be laid in the centre of the tank at different heights above the concrete floor. The streamlines are vertical at the sides of the tank which represent the midway position between drain tubes in a drainage system; thus the width of the tank is $2D$. By partitioning off part of the tank the linear dimensions can be scaled down by two-thirds and one-third; drain outlets are provided in the centre of these smaller tanks. A more extensive range of the ratio d/D can thus be made available.

The type of drain tube used was of stainless-steel mesh embodying a gravel pad to support the sand, similar to the wells used by Childs *et al.* (1953). When not lying on the floor, they were supported on tripods spaced at about 1 m. For the experiments in the large tank a drain tube of radius 9·0 cm. was used; in the smallest tank one of 5·0 cm. Use was not made of the intermediate tank. In both tanks the drain was not running full at low values of q/K and for high values of q/K the drain was smaller than that with the theoretical optimum radius. As explained by Childs and Youngs (1958) (cf. van Deemter, 1950; Engelund, 1951) the latter has the effect of raising the water table directly above the drain but has very little influence on the height of the water table midway

between the drains until the ratio of the drain radius to optimum drain radius becomes less than 0·2.

Experiments were conducted with various depths of drain with various rainfall rates. With a given rainfall imposed on the initially dry sand or on a lower rainfall rate, the drain discharge, measured by a weir-type flow-meter designed after a smaller model (Childs, 1940), gradually built up and asymptotically approached a steady value. The water-table height was determined at given time intervals during the build-up to the steady state by measuring the pressure distribution across a section of the tank at right angles to the drain tube by means of small pressure cells (null-point tensiometers) (O'Donnell *et al.*, 1958) and determining the locus where the pressure was atmospheric. When the steady state was reached, the spray system was either changed to a smaller rate or zero when the drain discharge decreased and the water table fell, or to a larger rate when the discharge continued to rise and the water-table height to increase. Throughout the experiments a check on the water temperature was maintained. In the large tank values of d/D used were 0·018 (on the floor), 0·078, and 0·138; in the small tank values of 0·210 and 0·390.

The saturated hydraulic conductivity of the sand was measured in various parts of the experimental tank by the two-well method (Childs, 1952; Childs *et al.*, 1953; Childs *et al.*, 1957). It was necessary to apply a correction factor to the values of the hydraulic conductivity obtained in these experiments to take into account the edge effects of the tank. The factor was determined in an electric analogue experiment using alternating current with dilute copper sulphate solution as the conducting medium and brass electrodes to represent the wells. The average value obtained for the saturated hydraulic conductivity of the sand contained in the large tank was 133 in./hr. (0·0937 cm./sec.). In the small tank where the sand was inevitably thoroughly disturbed for the laying of the drain, the value was 103 in./hr. (0·0728 cm./sec.).* These values are given for water at 20° C. and the hydraulic conductivity in a particular experiment was evaluated from these values and tables of the temperature dependence of the viscosity of water.

The Electric Analogue Experiments

The electric analogue is a practical means of solving Laplace's equation in a conducting sheet which is made to represent the ground-water zone in the hydraulic problem. Current is fed in uniformly along the 'water table' to simulate the rainfall and the drain is simulated by a contact at zero potential. In the experimental work reported here a commercial graphited paper ('Teledeltos'), as used by Edwards (1956), was used.

The experimental procedure varied slightly from previously reported analogue work in drainage. The conducting sheet was cut so that the

* These surprising experimental values for the hydraulic conductivities of the disturbed and undisturbed sand confirm the work of Childs *et al.* (1953) who showed that the hydraulic conductivity of the undisturbed sand, calculated from its moisture characteristic, was greater than that for the disturbed sand, similarly calculated.

electric current, analogous to the flow of water, was fed down strips to the part of the conducting sheet representing the groundwater zone, via rheostats and microammeters. A terminal shaped to represent the drain was cemented to the paper by means of colloidal graphite ('Aquadag') and provided the return lead in the circuit. Previously the strips to the water table have been cut with equal widths. This could involve large errors in the region of the drain where the slope of the water table may be large. To overcome this the current was fed to the 'water table' through strips of different widths and the current adjusted accordingly in each strip to maintain uniform current density at the 'water table'. A 20 cm. width of conducting paper was used to represent the half spacing of the drains and the current was fed down ten strips whose width decreased towards the drain, being 4·0 cm. at the midway position between the drains and only 0.5 cm. in the region over the drain. The potential distribution in the conducting sheet was determined by means of a probe with a small platinum wire contact and a potentiometer. The analogue was constructed by the method described by Childs (1943).

Hitherto the equipotentials and streamlines were plotted in order to obtain a value of q/K; this procedure was necessary because of the variability of the resistance of the paper used. The resistance of the 'Teledeltos' paper, while varying from day to day with the temperature and humidity of the atmosphere, was sufficiently constant over a sheet during an experiment to determine q/K from direct electrical measurements on the paper and not to adopt such a tedious method. When the analogue has been constructed, the 'water table' is at a potential proportional to the height above the drain. Thus we can write, following Childs (1943),

$$V_0 = Ah_e, \tag{1}$$

where V_0 is the voltage at a point on the 'water table' with respect to the drain terminal, A a constant, and h_e the height of the 'water table' above the drain terminal in the analogue. The potential at a point on the water table in the hydraulic case is represented in the analogue by the height h_e, so that 1 cm. head of water in the hydraulic case is represented by A volts in the analogue. Comparing Darcy's law,

$$q/K = \text{grad } \Phi \tag{2}$$

applicable to the hydraulic case, where Φ is the potential in cm. head of water, with Ohm's law,

$$IR = \text{grad } V \tag{3}$$

applicable to the analogue, where I is the current and R the resistance across the sides of a square in the conducting sheet, we have

$$q/K = \text{grad } \Phi = \frac{1}{A}\text{grad } V = \frac{h_e}{V_0}\text{grad } V = \frac{h_e}{V_0} IR. \tag{4}$$

Equation (4) gives the value of q/K in terms of the electrical and dimensional properties of the analogue constructed to represent the hydraulic model. It is not necessary to measure I and R to obtain a value of q/K, since the product IR is the gradient of the voltage down the conducting strips. In each experiment this gradient was determined

for three strips over a distance of 10 cm. and agreement found within 1 per cent.

The drain terminal in the analogue experiments was made to scale to represent the drain used in the hydraulic experiments. Starting with a high 'water table' at the midway position between the drains, the analogue of the hydraulic problem was constructed (Childs, 1943) and the value of q/K determined. This was repeated for lower water-table heights. A series of experiments were performed to obtain values of q/K for various values of h/D for different values of d/D.

Experimental Results

The results of the hydraulic and analogue experiments are shown in Figs. 1 and 2. In Fig. 1 values of h/D are plotted against q/K obtained

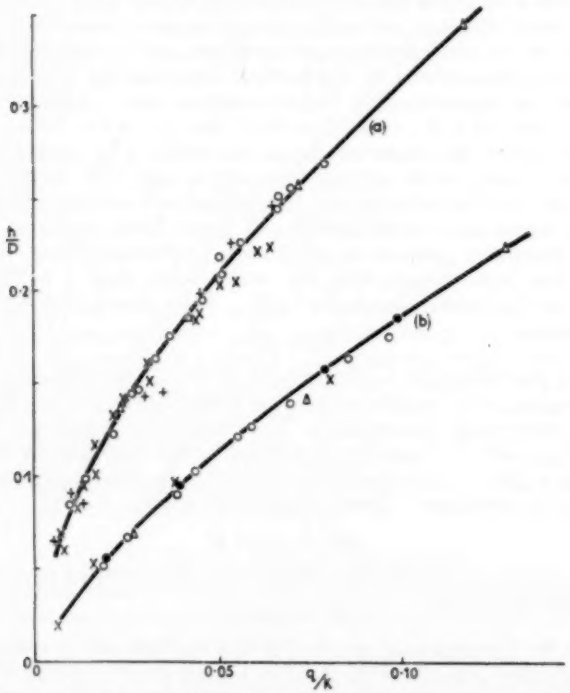

FIG. 1. The maximum water-table height plotted as a function of q/K for (*a*) $d/D = 0{\cdot}018$ (drain on the floor), and (*b*) $d/D \to \infty$. Hydraulic experiment, ○ steady state, × rising water table, + falling water table. Electric-analogue experiment Δ. Analytical solution (after Engelund) ●.

in the two experiments for the two extreme cases of the drain resting on the floor and of the largest value of d/D obtained—0·39 for the hydraulic case and 0·90 for the analogue case. In the latter curve the values given by Engelund (1951) for the impermeable floor at infinity

are compared. It is observed that agreement is obtained so we conclude that our experiments correspond (so far as practical purposes are concerned) effectively to an impermeable floor at an infinite depth. In Fig. 1 are also plotted values obtained for non-steady states and it is observed that these do not vary exceptionally from the steady state values.

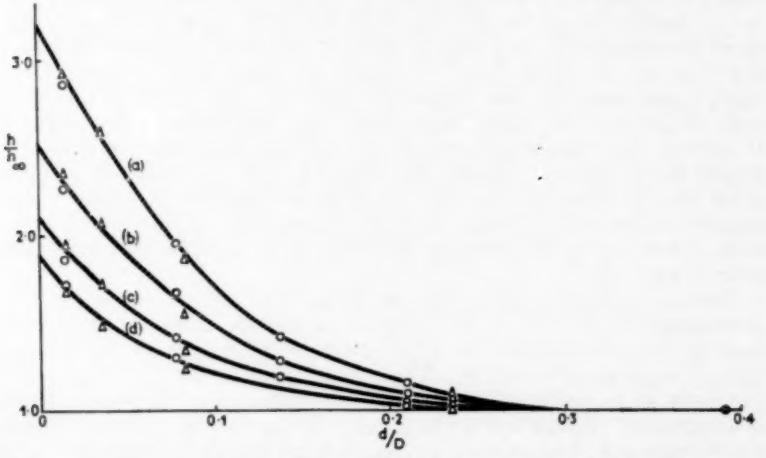

FIG. 2. The correction factor h/h_∞ plotted as a function of d/D; (*a*) $q/K = 0{\cdot}01$; (*b*) $q/K = 0{\cdot}02$; (*c*) $q/K = 0{\cdot}05$; (*d*) $q/K = 0{\cdot}10$. Hydraulic experiment ○. Electric-analogue experiment △.

In Fig. 2 is shown the correction factor h/h_∞ for values of q/K of 0·01, 0·02, 0·05, and 0·1, plotted as a function of d/D, to be applied to values of the height h_∞ of the water table above the axis of the drain tube midway between drains for the particular case of an infinite impermeable floor to obtain those for other values of d/D. The values given by Engelund (1951) were used in evaluating the ratio h/h_∞. Again, the hydraulic experimental values are compared with those obtained in the electric analogue.

Discussion

Although the experiments yielded the complete shape of the water table for each measurement taken, we have only reported the maximum water-table height variation with q/K. It is sufficient to say that the shapes agreed with those reported before by Childs (1943) for the electric analogue.

Fig. 1 indicates that good agreement was obtained in the hydraulic model and electric analogue experiments and also between these and Engelund's analytical solution for the case of the deep impermeable floor. This agreement is confirmation of all the hitherto available work on drainage theory. In the hydraulic case the conditions were not precisely those assumed in the analogue since it is impractical to keep

the drain just full of water. The maximum water-table height, however, remains unaffected at all values of q/K used with the experimental drain size.

Another result of consequence is the fit of the non-steady state values to the steady state curves. In the hydraulic experiments the value of q was obtained from the drain discharge so that the average value of q over the whole area was measured. Thus in the non-steady state q was the average value of the flux crossing the water-table boundary. The fit of the non-steady state values to the steady state curves confirms the experiments of Childs (1947) in which he showed by means of the electric analogue that the water table falls almost equally everywhere over the greater part of its descent when the infiltrating rain is stopped. It should be mentioned here that while the maximum water-table height during the non-steady state agreed with the steady state for a given average value for the flux across the water table, the effect in the neighbourhood of the drain was more pronounced—with a falling water table it was higher than the steady state value and with a rising water table it was lower.

The agreement between the hydraulic and electric analogue experiments is again observed in Fig. 2; a smooth curve can be drawn through the points of the two experiments when h/h_∞ is plotted against d/D for a given value of q/K. The curve indicates that the height h of the water table midway between drains decreases rapidly as the depth of impermeable floor increases from zero. When the ratio d/D approaches 0·3 the ratio h/h_∞ becomes unity; that is, the water-table height becomes the same as if the impermeable floor were at infinite depth. Thus the impermeable floor has no effect on the hydraulics of drainage for the values of q/K given when $d/D > 0{\cdot}3$. For lower values of q/K, however, the ratio h/h_∞ would not be expected to approach unity until d/D is much greater than 0·3, since it is seen that the ratio varies much more for small values of q/K than for large.

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